Mach Cones Induced by Di-Jets at RHIC and LHC: The Speed of Sound of Big Bang Matter

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Abstract A study of Mach shocks generated by fast partonic jets propagating through the quark-gluon plasma (QGP) is reviewed briefly. We predict a significant deformation of Mach shocks in central Au+Au collisions at RHIC and LHC energies compared to those created by a jet propagation through a static medium. Moreover, a new hydrodynamical study of jet energy loss is presented.

Key words Mach shocks, quark-gluon plasma, jet

1 Mach shocks induced by partonic jets

Recently, sideward peaks have been observed[1—4] in azimuthal distributions of secondaries associated with the high-$p_{\rm T}$ hadrons in central Au+Au collisions at $\sqrt{s}=200$GeV (see Fig. 1). In Ref. [5] such peaks had been predicted as a signature of Mach shocks created by partonic jets propagating through a QGP formed in heavy–ion collisions. Analogous Mach shock waves were studied previously in cold hadronic matter[7—11], in nuclear Fermi liquids[12, 13], and recently using a linearized fluid–dynamical approach[14]. It has been argued[6, 15] that Mach–like motions of quark–gluon matter can also appear via the excitation of collective plasmon waves by the moving color charge associated with the leading jet.

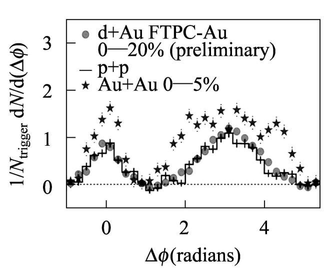

Fig. 1. Angular distribution of p+p and Au+Au collisions, normalized per trigger particle (from STAR collaboration[6], preliminary).

It is well known[16] that a point–like perturbation (a small body, a hadron or parton etc.) moving with supersonic speed in the spatially homogeneous ideal fluid produces the so–called Mach region of the perturbed matter. In the fluid rest frame (FRF) the Mach region has a conical shape with an opening angle with respect to the direction of particle propagation given by the expression[2)] $\widetilde{\theta}_{\rm M}=\sin^{-1}\left(\frac{c_{\rm s}}{\widetilde{\boldsymbol{v}}}\right)$, where $c_{\rm s}$ denotes the sound velocity of the unperturbed (upstream) fluid and $\widetilde{\boldsymbol{v}}$ is the particle velocity with respect to the fluid. In the FRF, trajectories of fluid elements (perpendicular to the surface of the Mach cone) are inclined at the angle $\Delta\theta=\pi/2-\widetilde{\theta}_{\rm M}$ with respect to $\widetilde{\boldsymbol{v}}$. Strictly speaking, the above formula is applicable only for weak, sound–like perturbations. It is certainly not valid for space–time regions close to a leading particle. Nevertheless, we shall use this

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2) Here and below quantities in the FRF are marked by tilde.

simple expression for a qualitative analysis of flow effects[6, 17]. Following Refs. [6, 14, 17] one can estimate the angle of preferential emission of secondaries associated with a fast jet in the QGP. Assuming the particle velocity to be $\widetilde{\boldsymbol{v}}=1$ and the sound velocity to be $c_{\rm s}=1/\sqrt{3}$ leads to $\Delta\theta \simeq 0.96$. This agrees well with positions of maxima of the away–side two–particle distributions observed in central Au+Au collisions at RHIC energies.

Following Refs. [6, 14, 17] we consider the case when the away–side jet propagates with velocity $\boldsymbol{v}$ parallel to the matter flow velocity $\boldsymbol{u}$. Assuming that $\boldsymbol{u}$ does not change with space and time and performing the Lorentz boost to the FRF, one can see that a weak Mach shock has a conical shape with the axis along $\boldsymbol{v}$. Transformation from the FRF to the c.m. frame (CMF) shows that the Mach region remains conical, but the Mach angle becomes smaller in the CMF

$$\tan\theta_{\rm M}=\frac{1}{\gamma_u}\tan\widetilde{\theta}_{\rm M}\,, \tag{1}$$

where $\gamma_u\equiv(1-u^2)^{-1/2}$ is the Lorentz factor corresponding to the flow velocity $\boldsymbol{u}$. This results in an expression for the Mach angle in the CMF

$$\theta_{\rm M}=\tan^{-1}\left(c_{\rm s}\sqrt{\frac{1-u^2}{\widetilde{v}^2-c_{\rm s}^2}}\right),\quad \widetilde{v}=\frac{v\mp u}{1\mp vu}\,. \tag{2}$$

Here, the upper (lower) sign corresponds to the jet's motion in (or opposite to) the direction of the collective flow. Considering an ultrarelativistic jet ($v\rightarrow 1$) leads to a simpler expression

$$\theta_{\rm M}\simeq\tan^{-1}\left(\frac{c_{\rm s}\gamma_{\rm s}}{\gamma_u}\right)=\sin^{-1}\left(c_{\rm s}\sqrt{\frac{1-u^2}{1-u^2c_{\rm s}^2}}\right), \tag{3}$$

with $\gamma_{\rm s}=(1-c_{\rm s}^2)^{-1/2}$. According to Eq. (3), $\theta_{\rm M}$ does in the ultrarelativistic limit not depend on the direction of flow with respect to the jet. The Mach cone becomes more narrow compared to a jet propagation in static matter. This narrowing effect has a purely relativistic origin. The Mach angle calculated from Eq. (3) is shown in Fig. 2 as a function of u for different sound velocities $c_{\rm s}$. Following Ref. [14], the value $c_{\rm s}^2=1/5$ is identified with the hadronic matter and $c_{\rm s}^2=1/3$ with ideal QGP composed of massless quarks and gluons. The value $c_{\rm s}^2=2/3$ is chosen to represent a strongly coupled QGP[18].

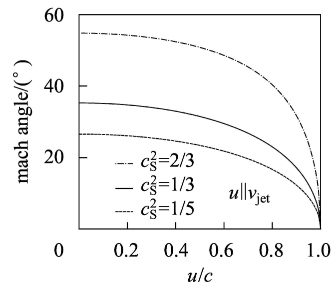

Fig. 2. Mach cone angles for jet propagating collinearly to the matter flow as a function of fluid velocity u. Different curves correspond to different values of sound velocity $c_{\rm s}$ (from Satarov et al.)[17].

2 A hydrodynamical study of jet energy loss

The STAR and PHENIX collaborations published the observation[1, 19, 20] that the away–side jet in Au+Au collisions for high-$p_{\rm T}$ particles ($4<p_{\rm T}$(trigger)$<$ 6GeV/c, $p_{\rm T}$(assoc)$>$ 2GeV/c) with pseudo-rapidity $|y|<0.7$ is suppressed as compared to the away–side jet in p+p collisions.

Commonly, this is interpreted as parton energy loss (jet quenching)[5, 21]. One part of the di-jets created in the collision escapes (near-side jet), the other one (away–side jet) deposits a large fraction of its energy into the dense matter.

We employ (3+1) dimensional ideal hydrodynamics to a hydrodynamical evolution of a sphere (using the SHASTA-algorithm[22]), and follow the time evolution of a fake jet that deposits all its energy and momentum in the initial state into a 2fm^3 spatial volume.

Initially, the medium has a radius of 5fm, an energy density of $e_0=1.68$GeV/fm^3 and a profile velocity increasing by radius as $\boldsymbol{v}(r)=0.02r/R$.

The jet's initial energy density increased by $\Delta e=$ 5GeV/fm^3 as compared to the medium and the jet material has an initial velocity of $v_x=0.96c$. We display the contour plots of the jet evolution at late state $t=12.8$fm/c for two different cases: Fig. 3 shows the evolution for an ultrarelativistic ideal gas EoS. Here, the jet is initially located in the region between $-5{\rm fm}<x<3{\rm fm}$, $|y|<0.5{\rm fm}$, $|z|<0.5{\rm fm}$. Fig. 4 depicts the evolution for a hadron gas with a first-order phase transition to QGP and a jet that is initially

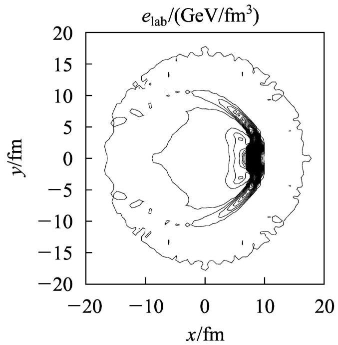

Fig. 3.　Contour plot of the laboratory energy density at $t=12.8\text{fm}/c$ for an ideal gas EoS.

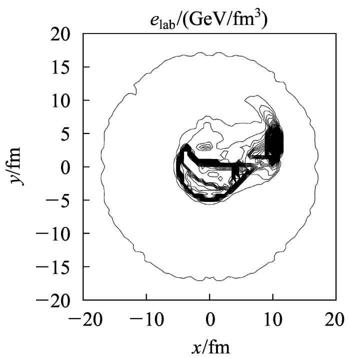

Fig. 4.　Contour plot of the laboratory energy density at $t=12.8\text{fm}/c$ for an hadron gas with first-order phase transition to QGP.

located in the retion between $-3\text{fm} < x < -1\text{fm}$, $2.5\text{fm} < y < 3.5\text{fm}$, $|z| < 0.5\text{fm}$.

The jet-induced shock front and a deflection of the jet in case of an EoS with phase transition to QGP is clearly visible.

3　Summary

We investigated properties of Mach shock waves induced by high–energy partons propagating through dense quark–gluon matter created in heavy–ion collisions. Assuming typical flow parameters expected in central collisions of nuclei at RHIC and LHC energies we showed that the shape of Mach regions are strongly modified as compared to the case of static (nonexpanding) medium.

Moreover, we presented a new hydrodynamical study of jet energy loss in (3+1) dimensional hydrodynamics.

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