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Drag force on a moving heavy quark with deformed string configuration

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Abstract

To study drag force on a moving heavy quark through a plasma, we use a deformed AdS space-time, in which deformation parameter c describes non-conformality in AdS/QCD. In this case, the quark is mapped to a probe string in the AdS space. Considering the probable contribution of the deformation parameter in the probe string, we apply a general form of c-dependent string ansatz in the drag force computation. Then, we find the acceptable value of this parameter as it satisfies QCD calculations. Using this result, we also discuss the diffusion constant which is in agreement with the phenomenological result for the non-relativistic limit. Also, we show that while in absence of a deformation parameter, the probe string is a strictly increasing function of radial coordinate, the c-dependent probe string has a maximum value versus z.

Keywords: AdS/QCD, drag force, deformation parameter

(Some figures may appear in colour only in the online journal)

1. Introduction

Studying the motion of quarks through QGP[4] during heavy ion collision is a distinctive feature of RHIC[5] data. In fact, when a high-energy parton propagates through the QGP, it quenches strongly. The drag force is related to the energy loss of the heavy quark, based on the interaction between the moving heavy quark and the medium. There is a connection between string theory and relativistic heavy ion collisions. The energy loss of the heavy quark is understood as the momentum flow along a moving classical string into the horizon. Perturbative calculation of many QGP quantities are currently out of our reach in the strong-coupling regime but gauge/gravity correspondence has been used to investigate observable quantities in various interesting strongly-coupled gauge theories where perturbation theory is not applicable.

AdS/CFT[6] conjecture originally relates the type IIB string theory on $AdS_5 \times S_5$ space-time to the four-dimensional $\mathcal{N} = 4$ SYM[7] gauge theory [1]. Also, many other studies represent a holographic description of AdS/CFT in which, a strongly coupled field theory on the boundary of the AdS space is mapped to the weakly coupled gravity theory in the bulk of AdS [2].

In this conjecture, the motion of a quark through a plasma is described by a mechanism in which there is a simple holographic picture dual to the probe moving quark in the plasma, as the quark is mapped to a probe string in the AdS space. So instead of studying the quark's motion in a strongly coupled system, one can simply consider the classical dynamics of a string in the gravity side. In AdS/QCD correspondence, replacing QCD[8] by $\mathcal{N} = 4$ SYM theory is an approximation according to the fact that after a critical temperature $\mathcal{N} = 4$, SYM theory may capture much of the dynamics of the QGP so that confinement and the chiral condensate disappear. This temperature is high enough to do this but low enough so that the 't Hooft coupling is still large.

[4] Quark gluon plasma.
[5] Relativistic heavy ion collider.
[6] Anti de sitter space-time/Conformal field theory.
[7] Super-Yang–Mills.
[8] Quantum chromo dynamics.

When a high-energy parton passes through the QGP, one may consider an external quark, in the framework of AdS/CFT [3]. Holographic drag force formalism is explained in [4–6] as the momentum rate flowing down to the probe string and is interpreted as drag force exerted from the plasma on the quark, and the quark is prescribed to move on the boundary of AdS_5. For the heavy quark, the most sensible trajectories are those with constant velocity relative to the reference frame and the rest frame of the plasma. The string trails out behind the quark and dangles into AdS_5. It is a holographic representation of the color flux from the external quark spreading out in the $3+1$ dimensions of the boundary theory.

Here, to clarify the motivation of our study, we need to clarify the bottom-up approach which suggests beginning with QCD and trying to match the properties of the dual gravity with known properties of QCD, so one starts from a five-dimensional effective field theory somehow motivated by string theory and tries to fit it to QCD as much as possible. The presence of probe branes in the AdS bulk breaks conformal symmetry and sets the energy scales. It would be interesting to consider some corrections in AdS_5 as the gravity dual to find more phenomenological results, also a question arises as to whether the string ansatz affects bulk properties. AdS/QCD is used to extract information of a four-dimensional strongly coupled gauge theory by mapping it on a five-dimensional gravitational theory. In this way, the produced model shares a few key features with QCD, which makes it more useful for phenomenology than AdS_5. In this paper, we will study the effect of the deformation parameter while it contributes to the probe string ansatz as well. Mentioning another example could also be useful for explaining the motivation of our case of interest: for studying drag force in presence of a magnetic field, one may consider a magnetized metric with some effects on the string ansatz. In our study, we try to discover if, in presence of a deformed AdS background, the string ansatz can be affected by the deformation parameter or not. Proceeding with this question we will try to find phenomenological results.

The motion of a quark has been studied in different literature [7–17] by AdS/QCD. In [18], the second correction of a radial coordinate has been discussed where the coefficient of such a correction is called the deformation parameter. Different effects of such a parameter on the physics of quark and its motion are studied in [19–21]. Also, the effect of the deformation parameter on drag force on a di-quark is considered in [22]. In recent years, different computations of drag force have been done [23–42].

This paper is organized as follows, in section 2 we review deformed AdS. We will compute the drag force in a deformed AdS in section 3. According to the obtained theoretical results, we will discuss some phenomenological aspects of the system in section 4. We will end with a conclusion in section 5.

2. Review of deformed asymptotically AdS background

In this section, we review the motivation for considering the second correction of the radial coordinate based on references [18, 19]. AdS/CFT correspondence is applied in strong interactions. It should be done by finding string description. Although the original conjecture of AdS/CFT was for conformal theories, some modifications produce mass gap, confinement and supersymmetry breaking in the gauge/gravity duality. In AdS/QCD, approach one may address the issue of the quadratic correction within the simplified models. It is useful to adopt the geometric approach and estimate the correction and compare the result with that of QCD.

The idea of modifying pure AdS geometry has been discussed in [43] in detail. Here we explain some headlines of motivation and approach. The interested reader is recommended to follow the calculation and detail in the main reference. The idea comes from the comparison of high energy correlators with operator product expansion (OPE) of two-point functions of QCD quark current. The question is, *what does the 5D dual of QCD look like?* In [44–52], the bottom-up approach succeeded in the study of the aspects the dual should explain, independently of a stringy set-up. The point is, QCD models, which are defined on truncated AdS space, lack power corrections in the correlator. Therefore, to incorporate more features of QCD, one may consider showing non-conformality in the metric. In [43], modification of the metric has been done in comparison with OPE, where the logarithm part of the OPE is produced by considering $\omega(z)=\frac{l_0}{z}$ in a purely AdS metric in conformal coordinates and string frame as,

$$ds^2=\omega^2(z)(\eta_{ab}dx^a dx^b-dz^2), \tag{1}$$

and the power corrections in OPE can be generated by deviations from conformality with a given power of z^{2d} in the metric. Later in [18, 19], the author estimated the quadratic correction of such a metric background and fixed the coefficient of said background. It was done by considering meson operators and looking for the corresponding vertex operators. The detail of those references and all steps and calculations are beyond the goals of our study and we will take advantage of their result. Briefly, from those studies, we find that in particular, one can consider a rather non-trivial structure of the quark configuration for the warp factor in the background metric. From the asymptotic linearity of Regge trajectories, one may understand that some backgrounds reduce to the standard AdS background in the UV but differ from it in the IR. It is known that some strong interactions would include the dominant square term at short distances as well as the dominant linear term at large distances. This assumption is quite acceptable in the classical limit of string theory where we are working. In this way, one can find aspects of different complicated warp and blackening factors.

We consider the following background metric (in the string frame),

$$ds^2=\frac{R^2}{z^2}h(z)\left(-f(z)dt^2+\Sigma_{i=1}^3 dx_i^2+\frac{1}{f(z)}dz^2\right), \tag{2}$$

where[9]

$$f(z) = 1 - \left(\frac{z}{z_h}\right)^4, \qquad h(z) = \mathrm{e}^{-\frac{c}{2}z^2}, \tag{3}$$

and the horizon is located at $z = z_h$ and the temperature of the black hole is $T = \frac{1}{\pi z_h}$. c stands for the coefficient of the second correction of the radial coordinate of the background, called the deformation parameter. Note at limit $c \longrightarrow 0$, the AdS_5 metric will be obtained. As c becomes more than zero, it deforms the AdS space. This model has some phenomenological benefits as it is a nearly conformal theory at UV, it results in linear Regge-like spectra for mesons, [18, 53] and results in a phenomenologically satisfactory description of the confining potential [19]. In the next section, we will use the deformed background.

3. Drag force on a moving heavy quark in a plasma with deformed gravity dual

Let us study the drag force in the deformed AdS_5 (2) while the configuration of the probe string attached to the moving quark is also affected by deformation parameter. We need a suitable ansatz to describe the behavior of the probe string attached to the moving quark. The massive heavy quark is prescribed to move along trajectories with constant velocity relative to the reference frame (the rest frame of the plasma). In general, one can consider a probe string which is described in the AdS by NG[10] action as,

$$S = -\frac{1}{2\pi\alpha'}\int \mathrm{d}^2\sigma\sqrt{-\det g_{\alpha\beta}}$$
$$g_{\alpha\beta} = G_{\mu\nu}\partial X_\alpha^\mu \partial X_\beta^\nu, \tag{4}$$

where σ^α are coordinates of the string worldsheet, $G_{\mu\nu}$ is the five-dimensional Einstein metric, and embedding of the string worldsheet in space-time is specified as an ansatz which should satisfy the assumption that at a late time, the steady-state behavior is obtained. We define the string ansatz with a probable contribution of the deformation parameter in a general form as follows,

$$\begin{aligned} X_0 &= t,\\ X_1 &= 0,\\ X_2 &= 0,\\ X_3(z, t) &= vt + \varepsilon(z) + \mathcal{O}(t),\\ \varepsilon(z) &= \zeta_0(z) + \left(\frac{c}{T^2}\right)\zeta(z),\\ X_4 &= z, \end{aligned} \tag{5}$$

where c is the deformation parameter in (2) and (3), so $\frac{c}{T^2}$ is a dimensionless variable. Also, $\mathcal{O}(t)$ are all terms that vanish at a late time and from now on we ignore them.

The equation of motion is obtained from (4) as,

$$\nabla_\alpha P_\mu^\alpha = 0 \qquad P_\mu^\alpha = -\frac{1}{2\pi\alpha'}G_{\mu\nu}\partial^\alpha X^\nu, \tag{6}$$

where ∇_α is the covariant derivative with respect to $g_{\alpha\beta}$. P_μ^α is the worldsheet current of space-time energy momentum carried by the probe string. Recall that μ is space-time index and α index stands for worldsheet coordinate. Considering a moving quark along an arbitrary direction as X_i, to calculate the flow of momentum $\frac{\mathrm{d}p_i}{\mathrm{d}t}$ down the string, one needs the following integral,

$$\Delta P_i = \int_{\mathcal{I}} \mathrm{d}t\sqrt{-g}\,P^{\,r}_{\,x^i} = \frac{\mathrm{d}p_i}{\mathrm{d}t}\Delta t, \tag{7}$$

where the integral is taken over some time interval $\mathcal{I}$ of length Δt. Drag force should be in the opposite direction of the motion, so the $\frac{\mathrm{d}p_i}{\mathrm{d}t}$ is a negative quantity. After some calculation, the drag force is obtained as,

$$\frac{\mathrm{d}p_i}{\mathrm{d}t} = \sqrt{-g}\,P^{\,r}_{\,x^i} = -\frac{1}{2\pi\alpha'}\pi_i, \tag{8}$$

where π_i is the conjugate momentum $\pi_i = \frac{\partial\mathcal{L}}{\partial X_i'}$.

Also, the rate of the energy loss for a moving quark with speed v is,

$$\frac{\mathrm{d}E}{\mathrm{d}t} = \sqrt{-g}\,P_t^r = -\frac{1}{2\pi\alpha'}\pi_t = -\frac{v}{2\pi\alpha'}\pi_i, \tag{9}$$

where $\pi_t = \frac{\partial\mathcal{L}}{\partial\dot{X}}$.

From (5) we have,

$$\begin{aligned} \dot{X}_3 &= v,\\ X_3' &= \varepsilon'(z)\\ \varepsilon'(z) &= \zeta_0'(z) + \left(\frac{c}{T^2}\right)\zeta'(z), \end{aligned} \tag{10}$$

where $'$ stands for derivative with respect to z.

Now, with (2), (3) and (5), the Lagrangian is given as,

$$\mathcal{L} = -\frac{R^2}{z^2}\mathrm{e}^{-\frac{c}{2}z^2} \times\sqrt{1 + f(z)\left(\zeta_0'(z) + \left(\frac{c}{T^2}\right)\zeta'(z)\right)^2 - \frac{v^2}{f(z)}}. \tag{11}$$

Then from (10) the conjugate momentum is written as,

$$\begin{aligned} \pi_3 = \frac{\partial\mathcal{L}}{\partial X_3{}'} &= \frac{\partial\mathcal{L}}{\partial\varepsilon'(z)} = \frac{\partial\mathcal{L}}{\partial(\zeta_0'(z) + \left(\frac{c}{T^2}\right)\zeta'(z))}\\ &= \frac{\partial\mathcal{L}}{\partial\zeta_0'(z) + \left(\frac{c}{T^2}\right)\partial\zeta'(z)}\\ &= \frac{1}{\frac{1}{\frac{\partial\mathcal{L}}{\partial\zeta_0'(z)}} + \left(\frac{c}{T^2}\right)\frac{1}{\frac{\partial\mathcal{L}}{\partial\zeta'(z)}}}. \end{aligned} \tag{12}$$

[9] The sign of the exponent in (3) is different from that of [18] because in the mentioned reference the author used the Euclidean metric. The Minkowskian metric of [18] is obtained via analytic continuation $x \longrightarrow -\mathrm{i}x$ together with $z \longrightarrow -\mathrm{i}z$.

[10] Nambu–Goto.

Using the (11) results in,

$$\frac{\partial\mathcal{L}}{\partial\zeta_0'(z)} = -\frac{R^2}{z^2}e^{-\frac{c}{2}z^2} \times\frac{f(z)\left(\zeta_0'(z)+\left(\frac{c}{T^2}\right)\zeta'(z)\right)}{\sqrt{1+f(z)\left(\zeta_0'(z)+\left(\frac{c}{T^2}\right)\zeta'(z)\right)^2-\frac{v^2}{f(z)}}},$$
$$\frac{\partial\mathcal{L}}{\partial\zeta'(z)} = -\frac{R^2}{z^2}e^{-\frac{c}{2}z^2} \times\frac{\left(\frac{c}{T^2}\right)f(z)\left(\zeta_0'(z)+\left(\frac{c}{T^2}\right)\zeta'(z)\right)}{\sqrt{1+f(z)\left(\zeta_0'(z)+\left(\frac{c}{T^2}\right)\zeta'(z)\right)^2-\frac{v^2}{f(z)}}}, \tag{13}$$

plugging (13) in (12) leads to,

$$\pi_3 = -\frac{R^2}{z^2}e^{-\frac{c}{2}z^2} \times\frac{f(z)\left(\zeta_0'(z)+\left(\frac{c}{T^2}\right)\zeta'(z)\right)}{2\sqrt{1+f(z)\left(\zeta_0'(z)+\left(\frac{c}{T^2}\right)\zeta'(z)\right)^2-\frac{v^2}{f(z)}}}. \tag{14}$$

Proceeding by solving (14) for the string ansatz we obtain,

$$\zeta_0'(z)+\left(\frac{c}{T^2}\right)\zeta'(z) =\pm\pi_3\sqrt{\frac{1-\frac{v^2}{f(z)}}{\frac{R^4}{4z^4}e^{-cz^2}f^2(z)-f(z)\pi_3^2}}, \tag{15}$$

and since the string trails out behind the quark, the acceptable sign in (15) is +. To avoid an imaginary string ansatz, the right-hand side of (15) should be real, which means the nominator and denominator should have a common root. By applying this condition, the final result for momentum is,

$$\pi_3 = \frac{R^2}{2z_h^2}\frac{v}{\sqrt{1-v^2}}e^{-\frac{c}{2}z_h^2\sqrt{1-v^2}}, \tag{16}$$

where $R^2=\sqrt{N}\alpha' g_{YM}$ and $z_h=\frac{1}{\pi T}$, T is Hawking temperature and its dual description is the temperature of the plasma. Then from (8) and (16), the final result for the drag force is

$$\frac{dp_3}{dt} = -\frac{\pi}{4}\sqrt{N}g_{_{YM}}T^2\frac{v}{\sqrt{1-v^2}}e^{-\frac{c}{2\pi^2T^2}\sqrt{1-v^2}} \tag{17}$$

and the rate of the energy loss from (9) is written as,

$$\frac{dE}{dt} = -\frac{\pi}{4}\sqrt{N}g_{_{YM}}T^2\frac{v^2}{\sqrt{1-v^2}}e^{-\frac{c}{2\pi^2T^2}\sqrt{1-v^2}}. \tag{18}$$

Also (16) with (15) together lead to,

$$\zeta_0'(z)+\left(\frac{c}{T^2}\right)\zeta'(z) = \frac{1}{z_h^2}\frac{v}{\sqrt{1-v^2}} \sqrt{\frac{\left(1-\frac{v^2}{\left(1-\left(\frac{z}{z_h}\right)^4\right)}\right)}{\left(1-\left(\frac{z}{z_h}\right)^4\right)\left[\left(\frac{1}{z^4}-\frac{1}{z_h^4}\right)e^{-c(z^2-z_h^2\sqrt{1-v^2})}-\frac{1}{z_h^4}\frac{v^2}{1-v^2}\right]}}. \tag{19}$$

Since in (19), $\zeta_0'(z)$ is derivative of string configuration at limit $c\longrightarrow 0$, using this condition we may write,

$$\zeta_0'(z) = \frac{vz^2z_h^2}{z_h^4-z^4}, \tag{20}$$

which leads to,

$$\zeta_0(z) = -\frac{v}{2}z_h\left[\tan^{-1}\frac{z}{z_h}+\ln\sqrt{\frac{z_h-z}{z_h+z}}\right]. \tag{21}$$

Later we will use the differential equation (19) to find the second term on the right-hand side of (5).

We will continue by discussing the value of parameter c with regard to QCD in the next section.

4. Discussions

Since the drag force is in X_3 direction, from now on we remove index 3 for simplicity. To find the acceptable value of the deformation parameter, we need to solve the equation (17). In the limit of large $Ng_{_{YM}}^2$ we have $\frac{p}{m}=\frac{v}{\sqrt{1-v^2}}$. So from (17), we find,[11]

$$\frac{dp}{dt} = -\frac{\pi}{4}\sqrt{N}g_{_{YM}}T^2\frac{p}{m}e^{-\frac{c}{2\pi^2T^2}\frac{m}{\sqrt{p^2+m^2}}}, \tag{22}$$

and the momentum of a moving heavy quark in a plasma falls by $\frac{1}{e}$ in a time [6],

$$t_0 = \frac{2m}{\pi\sqrt{N}g_{_{YM}}T^2}, \tag{23}$$

or

$$p(t) = p_1(0)e^{-\frac{t}{t_0}}. \tag{24}$$

[11] Although our gravity dual is not conformal, we use information from the conformal system. The reason is, firstly, QCD is not a conformal theory itself. Needless to remind that AdS/QCD is not an exact AdS/CFT duality but a very good approximation of that. Therefore even with $c=0$, one uses the limit of large Ng_{YM}^2 for QCD which is not conformal! Considering a non-conformal metric with $c\neq 0$ is nothing but describing QCD with a better gravity dual than AdS_5. So still the matched data on the boundary theory has not been changed phenomenologically.

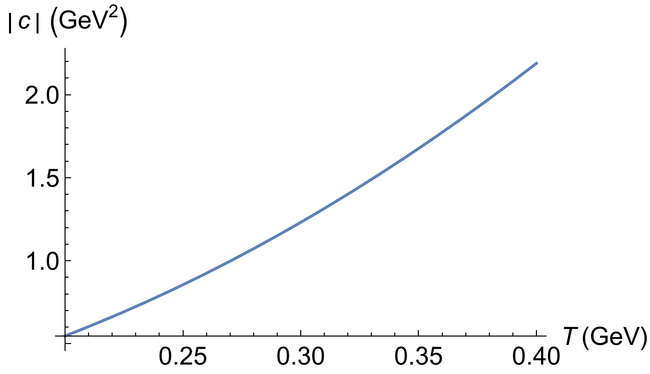

Figure 1. Behavior of the deformation parameter with respect to temperature, from (25).

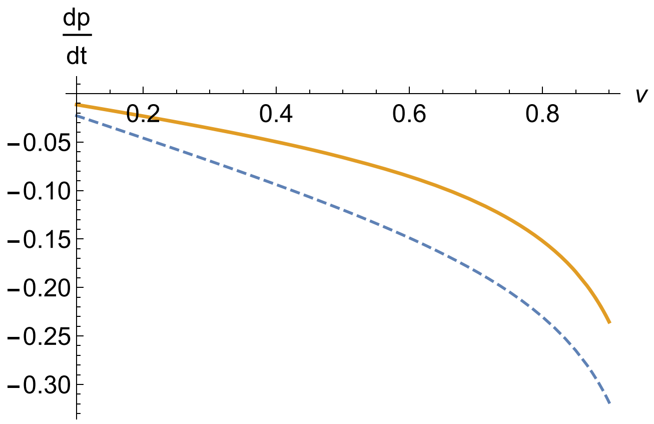

Figure 2. Drag force with respect to speed. Orange thick plot shows the drag force in absence of the deformation parameter, or $c \longrightarrow 0$ in (17) and dashed blue plot shows it in presence of the deformation parameter. The speed of light is taken as unit, $T = 250$ MeV and $Ng_{_{YM}}^2 = 5.5$ [6].

After plugging (24) into left side of (22), and by using (23) we integrate both sides from $t = 0$ to $t \to \infty$. So the relation between temperature of the QGP and deformation parameter on gravity side is given as,

$$c = -2\pi^2 T^2 \ln \frac{4m}{t_0 \pi \sqrt{N} g_{_{YM}} T^2} = -2\pi^2 T^2 \ln 2. \tag{25}$$

From above we write the exponential in (22) as,

$$e^{-\frac{c}{2\pi^2 T^2}\sqrt{1-v^2}} = 2^{\sqrt{1-v^2}}. \tag{26}$$

Plugging (25) and (26) in (17) and (18) both, the drag force and the energy loss are written as follows,

$$\frac{dp}{dt} = -\frac{\pi}{4}\sqrt{N} g_{_{YM}} T^2 \frac{v}{\sqrt{1-v^2}} 2^{\sqrt{1-v^2}}, \tag{27}$$

$$\frac{dE}{dt} = -\frac{\pi}{4}\sqrt{N} g_{_{YM}} T^2 \frac{v^2}{\sqrt{1-v^2}} 2^{\sqrt{1-v^2}}. \tag{28}$$

Recall that function $h(z^2)$, $h(0) = 0$ in (3) defines the deformation parameter in Euclidean space or Minkowskian space (see [18, 19, 39, 54] to compare c). In fact, c^2 appears in an energy momentum tensor [55]. So phenomenologically, the magnitude of c in (25) is the comparative parameter with QCD data. At the temperature $T = 250$ MeV of QCD [6], the deformation parameter in (25) is $|c| \simeq 0.84$ GeV^2, which is in agreement with the result of [56].

Another quantity that could be studied is the diffusion constant which is defined by [6]

$$D = \frac{T}{m} t_D, \tag{29}$$

where T is temperature, m is heavy quark mass and t_D is damping time which is related to drag force as follows,[12]

$$f \int_0^{t_D} dt = \int_p^0 dp, \tag{30}$$

therefore (27) is written as,

$$D = \frac{4}{\pi \sqrt{N} g_{_{YM}} T 2^{\sqrt{1-v^2}}}, \tag{31}$$

and by considering $\sqrt{N} g_{_{YM}} = \sqrt{5.5}$ as the best fit to QCD [6] we obtain

$$D = \frac{0.54}{T} \frac{1}{2^{\sqrt{1-v^2}}}, \tag{32}$$

as the diffusion constant of a heavy moving quark in a QGP with a deformed background.

For the heavy quark, at non-relativistic limit $v^2 \ll 1$ (in natural unit), the result of (32) is close to the phenomenological result of [57].

Figure 1 shows the behavior of the magnitude of deformation parameter with respect to the temperature of the plasma. The plot shows increasing temperature increases deformation parameter. In figure 2 we study drag force versus speed of the moving quark. The magnitude of the drag force increases with the increasing speed of the moving quark, also nonzero values of the deformation parameter strengthen the drag force. Figure 3 shows the string ansatz, $\varepsilon(z)$, in (a) the absence of the deformation parameter and (b) the presence of the deformation parameter. By solving the integral on the right-hand side of (19), numerically, we obtain the string profile $\varepsilon(z)$ in these plots. The contribution of the deformation parameter leads to finding the maximum value of $\varepsilon(z)$. Then, increasing z leads to an increasing $\zeta_0(z)$ in plot (a) as the string profile is a strictly increasing function of z, but in plot (b) at the nonzero deformation parameter, $\varepsilon(z)$ has a maximum value.

[12] There are differences between the current calculation and (23), (24) relations. In fact, to solve the equation we considered boundary conditions as both relaxation time and the momentum of heavy quark in SYM. As an interesting practice, one can compute t_D in the $SW_{T,\mu}$ model [39] and compare that result at limit $Q \longrightarrow 0$ with our result, then considering the value of c leads to the agreement.

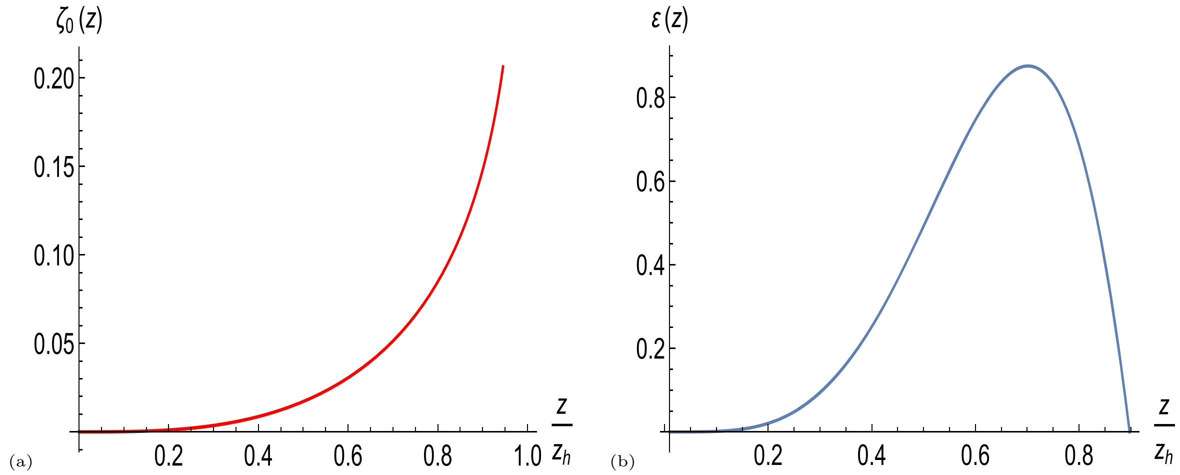

Figure 3. String profile at some constant speed (a) in absence of deformation parameter (b) in presence of deformation parameter.

5. Conclusions

We discussed the drag force on a heavy moving quark in a plasma with a deformed background and deformed probe string. We were motivated by the question that arises after applying a deformed AdS: what will happen if the deformation parameter appears not only in the background metric but also in the string ansatz? As parameter c deforms the AdS, what are the consequences for the probe string? To study this idea we applied a general ansatz for the probe string with the contribution of the deformation parameter. Phenomenologically and according to the drag force on moving heavy quark through a plasma, we tested the availability of the ansatz. At the temperature 250 MeV of QCD, we found the value of the deformation parameter as 0.84 GeV^2, which is in agreement with the QCD results. Studying the deformed string profile, we showed that while the c-independent string ansatz is strictly an increasing function of z, the c-dependent string ansatz finds a maximum value.

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