Transport coefficients and low energy excitations of a strongly interacting holographic fluid

Poovuttikul, N.

Author: Poovuttikul, N.
Title: Transport coefficients and low energy excitations of a strongly interacting holographic fluid
Date: 2017-11-16

More generally, we should study Quantum Field Theory from many points of view because of its many applications (and) in order to understand it better. Hopefully, we can learn how to improve its presentation – reformulate it.

N. Seiberg

6 Conclusion and outlook

In this thesis, three different classes of strongly interacting quantum field theories with holographic duals, classified by their global symmetries, have been studied. This work has focused on the transport coefficients which govern the low energy excitations of these systems. The results in this thesis contribute to three broad aspects of strongly interacting quantum field theory. Let me point out what they are, what have we learned about them in the course of this thesis and outline possible future research directions.

Possible universal relations of the transport coefficients

Two types of possible universal relations are investigated in chapter 3 and 4 of this thesis. The first relation is the bound on the ratio of the shear viscosity to the entropy (the KSS bound), which is widely believed to hold for a large class of systems. In a theory without translational symmetry, however, it was observed that the supposed "shear viscosity" extracted from the 2-point correlation function $\langle T^{xy}T^{xy}\rangle$ violates this bound. In chapter 3, we show that this quantity is not a shear viscosity due to the following reason. The holographic fluid which breaks translational symmetry is not a conventional relativistic fluid but a *forced fluid*, due to the presence of scalar fields which break translational symmetry. Thus, the constitutive relation and, consequently, the Kubo formula are modified. With the new constitutive relation, we can single out the *true shear viscosity* and show that it still violates the viscosity bound even at very weak momentum relaxation rate.

The second type of universal relations are relations between the anomalous conductivities and the anomaly coefficients. These are considered in chapter 4. We develop an independent proof for a large class of strongly interacting quantum field theories that the relations between the two quantities are exact, without relying on specific details of the Lagrangian. While, there is much evidences suggesting that the relations between anomalous conductivities and anomaly coefficients are exact, including a more conventional field theoretic proof, it is reassuring to find independent demonstration of the non-renomalisation nature of anomalous transports.

The result of chapter 3 is a clear demonstration that the relation between the shear viscosity and the entropy density is not a universal relation in theories without translational symmetry, such as those in condensed matter. It is an interesting question to investigate whether the KSS bound originates from something more fundamental, such as the quantum bound on the rate of entropy production which can still be applied in this scenario. There is a good amount of more recent works such as [42, 314–319] which explored this fundamental aspect and also its experimentally measurable consequences. In this regard, the anomalous transport is a promising area of research, strengthened by recent experimental realisations [320, 321]: the first direct measurements of anomaly coefficients! Since the materials in these experiments are described by weakly coupled QFT, it would be fascinating to see the same effect persist in strongly coupled systems to confirm the non-renormalisation nature of the anomalous conductivities and also to explore the consequences of quantum anomalies in a far-from-equilibrium behaviour.

Decoding hydrodynamic information from gravity

The results of chapter 3-5 can be obtained due to the fact that the transport coefficients are encoded in a theory of gravity. The most studied quantity is, of course, the shear viscosity. In many examples, it can be thought of as the absorption cross section of the low-energy graviton by the black hole. Moreover, it is encoded in the fluid description of the stretch horizon, thanks to the existence of radially conserved currents.

In chapters 4 and 5, we find new radially conserved currents associated to anomalous conductivities and MHD transport coefficients. Although, not all transport coefficients can be extracted from this method (namely the shear viscosity of the forced fluid in chapter 3 and the transverse resistivity and bulk viscosities in chapter 5), we present a simple way to extract these quantities despite the fact that they depend strongly on the bulk of AdS space. These formulae will be beneficial to future research as they greatly simplify the computation of the transport coefficients, thus allowing us to easily explore the landscape of strongly interacting quantum field theories.

From their relation to the radially conserved currents, we can categorise the transport coefficients into two kinds: those that only require the radially conserved currents and those that are not. With this information and the assumption that the radial coordinate of AdS corresponds to the energy scale, it is tempting to conjecture that the second kind of transport coefficients are controlled by specific details of renormalisation group flow while the first kind are encoded in some sort of "zero modes" which are independent of renormalisation group flow trajectories. Consequently, the transport coefficients of the first kind only depend on the IR fixed point and this could potentially lead us to new universal relations.

The fact that different parts of spacetime encode different QFT information is very intriguing. By decoding hydrodynamic data from certain regions of the spacetime, it is tempting to assume that every piece of spacetime contains information about quantum field theory. There are many recent works that try to come up with a unified framework to interpret any given region spacetime to the information in quantum field theory (see e.g. [322–326]. The approach we take in this thesis, on the other hand, is much simpler, as we only interested in finding regions of spacetime that encode the transport coefficients. Perhaps further investigation in this direction could give us profound insight regarding the precise field theory interpretation of AdS radial coordinate and the field theory data encoded behind the black hole horizon.

This research direction ties together ideas from theory of gravity, renormalisation group and leads to possibility that the gravity is a phenomenon that emerges from quantum field theory. It is exciting that we are able to witness developments that could revolutionised the way we understand QFT.

New symmetry, new hydrrodynamics and new phenomena

On a less other-worldly note, I would like to emphasise the power of the hydrodynamic constructions, particularly in chapter 5. We are able to construct unique effective theories, characterised purely by equations of state and a few transport coefficients, only by considering the global symmetry. This type of effective theory is applicable not only to low-energy dynamics of quantum theories but also to classical theories with the same global symmetries. Thus, the classification of modified hydrodynamics is beneficial not only to the realm of strongly interacting quantum fluids considered in this thesis, but also to the other areas of physics which involve collective behaviour.

Magnetohydrodynamics, studied in chapter 5, is an effective theory of a strongly interacting matter and a dynamical electromagnetic field with the higher-form symmetry as its guiding principle While the standard MHD formalism, which treats the matter sector and the electromagnetic field separately, is a very successful theory, it is only valid in the regime where the magnetic field is weak. The formalism in chapter 5 does not distinguish between the two sectors. Thus, it allows us to explore the scenario where both the magnetic field and the interaction strength within the matter sector are strong. We focus on a theory where the matter sector is a strongly interacting quantum field theory with a holographic dual and explore the entire range of the magnetic field strength.

By doing this, we find several new qualitative features of waves in MHD as we vary the strength of the magnetic field and the angle between the wave propagation direction and magnetic field lines. Among many observations, we emphasise the role of the dissipative terms in turning the MHD sound modes into new diffusive modes as one varies the propagation direction. This is a phenomena which cannot be observed in an ideal magnetohydrodynamics, which is commonly applied in the phenomenology of plasma. Our results also reveal various qualitative features of MHD waves at strong magnetic field that are vastly different from those at weak field.

The role of holographic duality in this chapter is twofold. First, it can be used to create a state of plasma, which is thermodynamically stable throughout the entire range of the magnetic field strength. Second, the computation of transport coefficients in the gauge/gravity duality framework is much easier compared to the weakly coupled QFT computation. We expect that many quantitative features in chapter 5 also persist in the perturbative regime where the interaction within the matter sector is weak. It is one of our top priorities to confirm this conjecture. This would allow us to make easier contact with experiment (such as nuclear fusion experiment) or astronomical observations of phenomena which are believed to be described by magnetohydrodynamics (see e.g. Fig.6.1).

Last but not least, I would like to point out another promising aspect of global symmetry in hydrodynamics which emerges from attempts to combine dissipative effect with the Wilsonian effective action. It turns out that, as a consequence of fluctuation-dissipation relations, the effective action is invariant under an emergent supersymmetry (see e.g. [329] for early developments and [275, 330] for more recent ones). It would be very interesting to explore consequences of this large global symmetry group on observable effects, holographic duality and strongly interacting quantum field theory.

Let me conclude these adventures in the realm of strongly interacting QFT. (Global) Symmetry is a beautiful concept that guides us through this unknown land. It is a backbone of modern theoretical physics, including everything in this

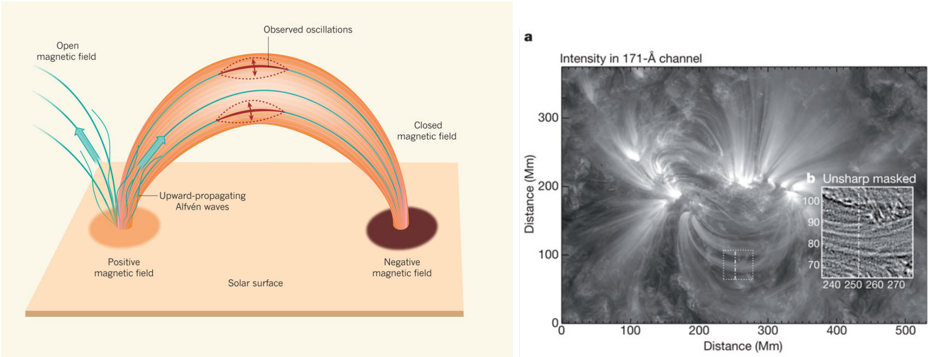

Figure 6.1. One of the MHD modes, the Alfvén wave, can be thought of as an oscillation mode of the magnetic field lines as depicted in (LEFT). It was postulated to be responsible for heat transfer in the solar corona and was recently observed by Hinode spacecraft in [327]. The images are taken from [327, 328]

thesis. Regardless of how we change our view of QFT in the future, I believe that the global symmetry will always play a central role.