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The Universe in a Helium Droplet

by G.E. Volovik

Review by P.V.E. McClintock of CPH/2002/001398

Physicists should only embark on Grisha Volovik's book when feeling strong. This is not so much on account of its size – 500 pages arranged in 32 chapters divided into 7 sections, plus Conclusions – but because they will find some of their most cherished beliefs being severely challenged.

The author brings together three huge areas of physics, points out what they possess in common, and uses what is well understood in one area to illuminate what remains unknown in another. He takes the coldest macroscopic physical system (superfluid helium), together with the hottest one on which experiments can be performed (elementary particles), and the almost inconceivably hot (cosmology just after the Big Bang), and weaves them together theoretically into a coherent whole. He starts from the hypothesis that low energy properties are governed mainly by topology and symmetry, notes that the A-phase of superfluid ^{3}He is topologically very similar to the quantum vacuum of the Universe, and develops the analogy from there. This may sound fanciful, even diletante, but in reality the book is quite otherwise. It is detailed, scholarly, extraordinarily erudite, closely argued, utterly original, and very, very serious.

Consider superfluid helium (either the common isotope ^{4}He or the much rarer one ^{3}He) at a very low temperature. It then behaves much like a vacuum, exerting no drag on a moving object but renormalising its mass. Quasiparticles (e.g. phonons) exist as collective excitations of this vacuum, and travel at a characteristic velocity, that of sound. On this level, the existence of the helium atoms and their mutual interactions is totally irrelevant. Practically all properties of the system can be described in terms of an effective theory that takes no account of the microscopic structure: Landau-Khalatnikov theory for ^{4}He and a development of Landau Fermi liquid theory for ^{3}He. At the lowest energies, the atomic structure is relevant only in that it determines "fundamental" constants such as the velocity of sound u. Yet liquid helium can also (albeit with effort) be described at a deeper level, in terms of the inter-atomic potential: this would represent a Theory of Everything (ToE) for helium. In these terms, properties like sound propagation and superfluidity would be seen as "emergent phenomena" that would be hard to predict from the ToE.

The similar symmetries of superfluid ^{3}He-A and the Universe mean that there are close correspondences between the topological defects of both these vacua. Cosmic strings, monopoles, domain walls, solitons etc in the Universe have their helium counterparts as quantized vortices, hedgehogs, domain walls, solitons, etc. in the superfluid. Unlike the quantum vacuum of the Universe, however, we already have a ToE that in principle underlies all phenomena in superfluid ^{3}He-A. So in the latter case we can look at the problem from both directions. Volovik's idea is that this detailed understanding can provide insight and enhanced perspective on the Universe. He develops the helium/universe analogy in great detail and, remarkably – or perhaps unsurprisingly given their close correspondences in symmetry – finds that Lorentz invariance and almost all the features of the Standard Model emerge at low energies.

The analogy also offers an astonishingly simple explanation of the problem of the cosmological constant – which is smaller than expected theoreticaly by many orders of magnitude. Volovik points out that, for helium, the vacuum energy can be either positive or negative, depending on whether it is a gas or a liquid with a surface. If the Universe is pictured as being like a quantum liquid in equilibrium, its vacuum energy must vanish – unless it is a droplet, in which case there will be surface corrections scaling inversely with the size of the droplet. Vacuum dark pressure, which is measured by the cosmological constant, indeed scales as the inverse square of the size of the Universe.

Note that, in the effective theory of superfluid helium, u plays the role of a fundamental constant. But, for the ToE, u is not fundamental at all. Rather, the fundamental constants of the ToE could be taken as $\hbar$, ϵ_0 and r_0 to specify the depth/size of the Lennard-Jones potential, and the helium atomic mass m. But two of these so-called fundamental constants, ϵ_0 and r_0, can of course be determined from a yet more fundamental ToE, atomic physics, for which the fundamental constants are $\hbar$, the electronic charge e and the electronic mass m_e. In turn, e and m_e are determined by an even higher energy ToE, the Standard Model of particle physics. Volovik comments: “Such a hierarchy of ‘fundamental constants’ indicates that the ultimate set of fundamental constants probably does not exist at all.”

Volovik infers that we exist in the low-energy corner of a larger and more complex reality. In the same way that an imaginary entity “living” in superfluid ^{3}He-A could predict all easily observable phenomena from Landau Fermi liquid theory, without needing to know anything whatever about molecular or atomic or sub-atomic physics, all of our theorising to date including relativity and the Standard Model may just represent effective theories. Some implications of this approach are: that because gravitation is just an effective theory, there is not much to be gained by quantising it; that Lorentz invariance is another low-energy feature and a non-relativistic regime will emerge at high enough energies; that the velocity of light may not be fundamental (any more than the velocity of sound in the superfluid vacuum is fundamental); and that the equivalence principle and gauge invariance are probably inexact.

It is impossible in a few lines to do justice to a work of scientific imagination on the scale that Volovik has produced. It provides his personal perspective of the physical Universe, worked out in quantitative detail, of which only a few samples have been mentioned briefly above. Is he right? Only time will tell, but many of his arguments have the ring of truth about them for me. His picture taken as a whole is a coherent vision that fits well most of the facts that are known from experiment. At the very least the breadth of this vision is refreshing and highly thought provoking. In his Foreword, James Bjorken remarks: “So far, this is not respectable territory, so there is danger to the young researcher in venturing within – working on it may be detrimental to a successful career track...”! But he also comments on the high adventure and great rewards if the ideas turn out to be correct. If they are, we will all need to start rethinking our own perspectives of the Universe.

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Universe in a Helium Droplet - Free download as PDF File (.pdf), Text File (.txt) or view presentation slides online. Volovik's Induced Gravity theory based on the notion of a quantum vacuum condensate of two components, similar to superfluid He-3 and He-4.Â Description: Volovik's Induced Gravity theory based on the notion of a quantum vacuum condensate of two components, similar to superfluid He-3 and He-4. Date uploaded. Aug 14, 2012. Universe in a helium droplet. topological Fermi liquids: from Migdal jump. to topological Khodel fermion condensate.Â The review starts by a presentation of the Dirac magnetic monopole and goes on with the Berry phase in a two-level system and the geometrical/topological band theory for Bloch electrons in crystals. Next, specific examples of tight-binding models giving rise to lattice versions of the Dirac equation in various space dimension are presented: in 1D (Su-Schrieffer-Heeger and Rice-Mele models), 2D (graphene, boron nitride, Haldane model) and 3D (Weyl semi-metals). Then its pressure must vanish, unless it is a droplet â€“ in which case there will be surface corrections scaling as an inverse power of the droplet size. But vacuum dark pressure scales with the vacuum dark energy, and thus is measured by the cosmological constant, which indeed scales as the inverse square of the â€˜sizeâ€™ of the universe. The problem is â€˜solvedâ€™. But there is some bad news with the good.