LETTERS TO PROGRESS IN PHYSICS

Commentary Relative to the Seismic Structure of the Sun: Internal Rotation, Oblateness, and Solar Shape

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Helioseismological studies have the ability to yield tremendous insight with respect to the internal structure and shape of the solar body. Such observations indicate that while the convection zone displays differential rotation, the core rotates as a rigid body. The latter is located below the tachocline layer, where powerful shear stresses are believed to occur. Beyond simple oblateness, seismological studies indicate that the Sun displays significant higher order shape terms (quadrupole, hexadecapole) which may, or may not, vary with the solar cycle. In this work, such seismological findings are briefly discussed with the intent of highlighting that 1) the differential rotation of the convection zone, 2) the rigid body rotation of the core, 3) the presence of the tachocline layer and 4) the appearance of higher order shape terms, all lend support to the idea that the solar body is composed of material in the condensed state. In this regard, the existence of the tachocline layer in the solar interior and the solid body rotation of the core constitute the nineteenth and twentieth lines of evidence that the Sun is condensed matter.

> *In brief, every rotating body conducts itself either as if it is it were purely liquid, or as if it were purely gaseous; there are no intermediate possibilities. Observational astronomy leaves no room for doubt that a great number of stars, perhaps even all stars . . . behave like liquids rather than gases.*
>
> Sir James Hopwood Jeans, 1929 [1]

For much of his life, James Jeans believed that stars were rotating liquids [1, 2]. On the basis of the tremendous abundance of binary systems [2], he had claimed that there could be no doubt of their condensed nature. Yet, in the paragraph which followed that quoted above, Jeans also argued: *"we are totally unable to check our theoretical results by observation"* [1, p. 219]. This apparent contradiction was previously highlighted by Alan B. Whiting [3, p. 209]. Eventually, Jeans lost sight of the observational evidence which had so convinced him. By 1944, he had abandoned liquid stars [2,4] and so did astrophysics; although in the 1960s, Subrahmanyan Chandrashekar would devote nine years of his life to the study of rotating liquid bodies [4,5]. With time however, astronomy would add to the arsenal of evidence that the Sun was liquid (see [6–8] and references therein).

Seismology, the study of low frequency waves within condensed matter, would also contribute to our understanding [9, 10]. Indeed, the mere application of seismology to the Sun has been heralded as a proof for condensed matter (see proof 5 in [8]). It is not reasonable to claim that the solar photosphere, with a density of only 10^{-7} g/cm^3 [11], can act as a mere optical illusion relative to the presence of a distinct surface [12], while at the same time forming the confines of a resonant cavity for seismological studies [13]. The author has already argued that it is not possible to conduct seismological observations on a surface whose density remains inferior to some of the best vacuums on Earth [8], despite the apparent agreement with the gaseous solar models [14, 15]. Seismology has been, and always will remain, linked to the study of condensed matter.

In this regard, seismology has brought some interesting insight into the internal structure of the Sun. The fact that the convection zone undergoes differential rotation appears well established, as is the presence of a prolate tachocline layer [9,10]. The tachocline region acts as a shear layer which separates the differential rotation in the convection zone from the solid body rotation observed in the solar core. Shear forces imply area and surface. As such, the presence of the tachocline layer in the solar interior is now advanced as the nineteenth line of evidence that the Sun is condensed matter. Furthermore, the solar core is rotating as a solid body (e.g. [10]) and this remains impossible for a gaseous object. Solid body rotation involves strong internal cohesive forces which gases cannot possess. Consequently, the solid body rotation of the solar core is now invoked as the twentieth line of evidence that the Sun is condensed matter.

Finally, it is well established that the Sun is not perfectly spherical but oblate (see [15, 16] and references therein). Indeed, the presence of solar oblateness could be related to Jean's arguments for liquid stars [2]. Since the creation of an oblate object requires internal cohesive forces which can only characterize a liquid or solid rotating sphere, solar oblateness has already been invoked as the eighth line of evidence that the Sun is condensed matter [8]. Yet, the solar shape is even more complex, characterized by quadrupolar and hexadecapolar terms [16], the latter of which appears dependent on the solar cycle. These additional features on the solar sphere served to complement the eighth line of evidence (solar shape [8]) that the Sun is condensed matter.

Dedication

This work is dedicated to Bernadine Healy†, Reed Fraley, Joan Patton, Bradford Stokes, and Kamilla Sigafoos for their administrative leadership in helping to create the world's first Ultra High Field MRI system at The Ohio State University.

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