PHYSICAL PROPERTIES OF LIQUID FE ALLOYS AT HIGH PRESSURE AND THEIR BEARINGS ON THE NATURE OF METALLIC PLANETARY CORES: IMPLICATIONS FOR THE EARTH, MARS AND THE GALILEAN SATELLITES.

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We report new high pressure data on liquid Fe-17wt% Si and Fe-27wt%S alloys. X-ray diffraction data are interpreted in the light of density measurements of liquid Fe-S alloys at high-pressure [1] and of a recent investigation of structural changes in liquid Fe at high pressures and high temperatures [2].

The paper is organised as follows: first the experimental data are exposed, and are then used to discuss 1) the potential nature of the light elements in the terrestrial outer core, 2) the physical state, solid vs liquid, of the Martian core with regard to its moment of inertia, and 3) internal models of small planetary bodies interiors such as the galilean satellites.

1 High pressure experimental results

High pressure experiments conducted on liquid Fe-S alloys have revealed that the presence of sulfur strongly affects the liquid properties, particularly its compressibility [1]. A large volume apparatus (Paris-Edinburgh press [3,4]) was used, allowing access to the P-T range of 0-6 GPa and 1500-2300 K. Experiments were carried out at the ESRF ID30 synchrotron X-ray beamline (Grenoble, France). It was shown that increasing the amount of sulfur in liquid iron decreases the bulk incompressibility (K₀) by -2.5 GPa per 1 weight% of S, for a planetary S plausible content of 0-20wt%. For higher S contents, this dependency decreases down to -0.2 GPa/wt%S.

We report here the main statement of the comparison between radial distribution functions of molten Fe, Fe-27wt%S and Fe-17%Si (Fig. 1-A). At similar Tm, normalized temperatures (Tm, melting temperature), Fe-27%S melts do not present any local order beyond 6 A, and even the two first shells of neighbouring atoms (≈ 2.5 A and ≈ 5 A) exhibit a much less structured signal. Consequently, the number of allowed configurational states in melted Fe-27%S is probably much higher than in pure Fe melt, providing a rationalized explanation for their larger compressibility. The observed relationship between the compressibility and the microscopic structure of the liquids can thus be used to infer qualitatively macroscopic properties from diffraction data only. X-ray diffraction data on liquid Fe-17%Si show that, in contrast to Fe-27wt%S, this liquid is structurally closed to pure liquid Fe (Fig. 1-B). As Fe-17%Si melts display a pure Fe-like local order, it probably also implies very close macroscopic properties such as the bulk compressibility.

2 Geophysical implications

The present experimental results show that sulfur strongly affects the structure of liquid iron and its bulk modulus. If ever S is present in non negligible quantities in liquid planetary cores, it can be revealed by comparing both density (density deficit vs pure Fe) and compressibility profiles extracted from seismic data [5]. In contrast, Si is “silent” as far as compressibility is concerned and its presence can only be probed by comparing computed and observed density profiles. The chemical composition of planetary liquid cores should indeed be determined not only from density data, mostly a function of the atomic mass, but also from compressibility data, truly dependent on structural properties. So far, it is legitimate to consider that the strong effect that we measured of S on K₀ persists over the megabar pressure range, unless Fe-S liquids encounter (1st order) structural changes still to be discovered at high pressure. Decompression of PREM core properties along an adiabatic temperature profile lead to (K₀, K''₀) values for the outer core ranging from (105.3 GPa, 6.42) to (152.5 GPa, 4.22) [6]. All of these values are significantly higher than the bulk modulus of pure liquid iron: 85 GPa at 1810 K [7]. The alloying of S to liquid Fe in the terrestrial outer core would even increase the compressibility. The observed relationship between the compressibility and the microscopic structure of the liquids can thus be used to infer qualitatively macroscopic properties from diffraction data only. X-ray diffraction data on liquid Fe-17%Si show that, in contrast to Fe-27wt%S, this liquid is structurally closed to pure liquid Fe (Fig. 1-B). As Fe-17%Si melts display a pure Fe-like local order, it probably also implies very close macroscopic properties such as the bulk compressibility.

Figure 1: Radial distribution functions for liquid Fe-27wt%S (A) and Fe-17wt%Si (B). All g(r) functions have been artificially spaced.
content in the core. The physical state, solid vs liquid, of the Martian core is still a matter of debate. Here, we quantify the S-effect on the planet properties in both cases. The most important difference concerns the moment of inertia: 0.363 for a solid Fe-Ni-16.2%S core versus 0.356 for a liquid Fe-Ni-16.2%S. Since the recent Martian missions, Mars Pathfinder and Mars Global Surveyor, the moment of inertia has been more precisely determined, at 0.365±0.02 [14,15]. Therefore, the new data obtained on Fe-S liquid alloys tend to favour a solid state for the Martian core.

Our experimental pressure conditions (density and structure of liquid Fe alloys) are also directly relevant to the interior of a small planet, typically a galilean satellite. The question we address here, is whether or not it is important to consider the S-effect on the equation of state of potential core materials while calculating internal models of small planetary bodies such as the galilean satellites.