Equation of State of Iron and Iron Sulfide with Implications for Jupiter's Galilean Satellites

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Introduction

Jupiter's four Galilean satellites (Io, Europa, Ganymede, and Callisto) have been the focus of intense interest as a result of the recent Galileo spacecraft mission to this system. These four satellites are large bodies (Table 1). The Jovian system can, in many respects, be considered a miniature version of our own solar system. Among the most intriguing findings from the Galileo mission are the possibility of a liquid ocean on Europa and the likelihood that a geodynamo is present on Ganymede (and possibly other satellites as well).

Table 1. Data on Jupiter's four satellites, Mars, and the moon.[a]

Planetary bodies	Radius (km)	Mean density (g cm^{-3})	C/MR^2
Io	1818	3.518	0.371
Europa	1561	3.014	0.346
Ganymede	2634	1.936	0.315
Callisto	2408	1.839	0.359
Mars	3390	3.933	0.366
Moon	1740	3.34	0.395

[a]Data for satellites are from Reference 1. C = moment of inertia, M = mass, R = radius.

The moments of inertia of the satellites reveal that they are all at least partially differentiated bodies. In fact, the moment of inertia for Ganymede is the lowest in the solar system. Existing geophysical data indicate that the basic structures of Europa and Ganymede consist of an outer ice layer, a silicate mantle, and an iron-dominated core. Io, the most volcanically active body in the solar system, has a silicate crust and is also expected to have a metal core. However, existing interior models [2-5] are poorly constrained, in part because they are not based on direct measurements of the densities of possible core constituents under Galilean interior conditions. Here we report direct measurements of the crystal structure and equation of state of iron (Fe) and iron sulfide (FeS) under pressure-temperature (P-T) conditions appropriate for the Galilean satellites.

Methods and Materials

In situ energy-dispersive x-ray diffraction (XRD) experiments were performed at beamline 13-BM-D of the GeoSoilEnviro Consortium for Advanced Radiation Sources (GSECARS) sector. Starting materials were powdered stoichiometric Fe and FeS. FeS was synthesized in an evacuated glass tube at a high temperature of 1000K for 3 d. An electron microprobe analysis was performed and confirmed to give stoichiometric $Fe_{0.498}S_{0.501}$. The sample charge consisted of layers of Fe and FeS separated by a layer of NaCl, which was used as a pressure calibrant [6]. NaCl was also mixed with Fe to impede grain growth at high temperatures. A $W_{0.94}Re_{0.06}$-$W_{0.75}Re_{0.25}$ thermocouple was embedded in the NaCl layer without any contact with Fe and FeS layers to prevent any chemical reaction during high P-T experiments. The sample was pressurized by using the 250-ton press with the T-cup multianvil apparatus [7]. The incident x-ray beam was collimated to $100 \times 300\ \mu m$, and diffraction patterns were recorded by using a germanium solid-state detector at a fixed angle, $2\theta = 5.198°$. X-ray peaks were recorded over the energy range of 30-120 keV. Each spectrum was collected for at least 300 s.

Results and Discussion

We collected x-ray diffraction spectra covering a pressure range from ambient to 14 GPa and a temperature range from 300 to 1300K. Representative spectra for FeS are shown in Fig. 1. Four separate phases of FeS have been identified, consistent with previous studies [8, 9]. Figure 2 shows the P-T distribution of our data for FeS and the phase boundaries determined in this study. The boundary between FeS IV and V has been controversial on the basis of previous studies [8, 9]. Our results are consistent with the boundary given in Ref. 9 and with higher-pressure data as well [10]. Our results show conclusively that FeS V is the relevant phase for the Galilean satellite cores. Determination of the pressure-volume-temperature equations of state for these two materials are in progress. We expect that the results will
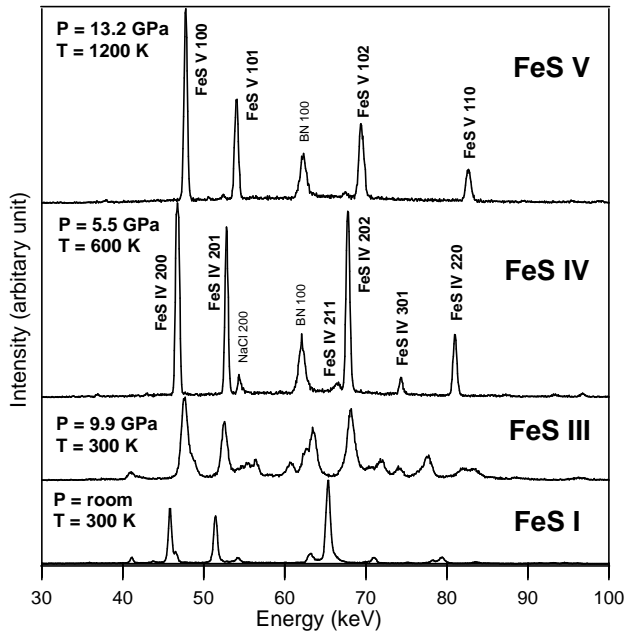
FIG. 1. Representative spectra of four phases of FeS observed in our experiments at indicated pressures and temperatures. FeS I has a NiAs-type structure with a (Ö3a, 2c) hexagonal unit cell. FeS III has a monoclinic unit cell. FeS IV has a NiAs-type structure with a (2a, c) unit cell. FeS V also has a NiAs-type structure with an (a, c) unit cell. Each peak is labeled with its Miller indices. One boron nitride peak labeled BN(100) arising from the sample assemblage was also recorded.

FIG. 2. Phase stability fields of FeS I, III, IV, and V compared with estimated P-T range of Galilean satellite cores.

lead to improved models for the interior structures of these satellites.

Acknowledgments

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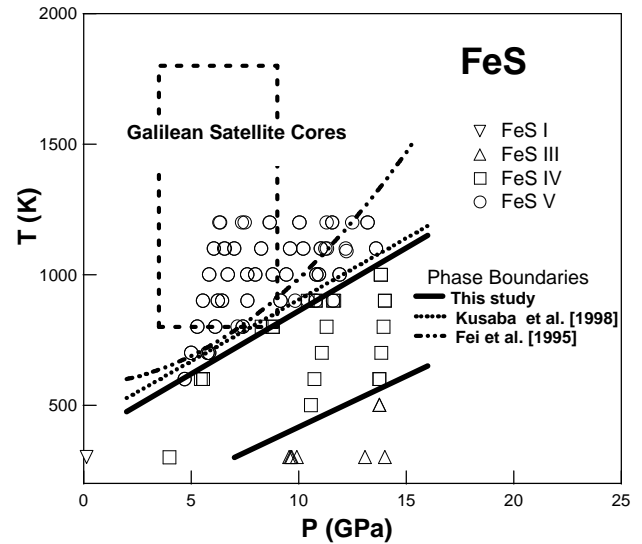[4] J. D. Anderson, E. L. Lau, W. L. Sjogren, G. Schubert, and W. B. Moore, "Gravitational constraints on the internal structure of Ganymede," Nature **384**, 541 (1996).
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