Ions help decipher the messages from the early solar nebula

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It was a good beginning: the first sample we investigated with Ernst in 1985 had very large Ti and Ca isotope anomalies, the first ones reported for a CO chondrite CAI [1]. It consisted of hibonite and hercynite with strongly fractionated trace element abundances and with those in hercynite being much too high for a spinel (Fig.1). Obviously, the hercynite carried a trace element abundance signature of a super-refractory precursor. This was an early solid case for a solid-fluid interaction - with the fluid very likely being the solar nebula. Now we know that **metasomatism** was omnipresent in the early solar system and played a fundamental role in the genesis of meteoritic rocks by transforming minerals or changing their chemical and isotopic compositions - a fact unfortunately still neglected by most meteoriticists.

Another very important result of our work with Ernst is the recognition of the role nebular silicate liquids played in the genesis of meteoritic rocks. Such **"universal" liquids** [2] can be traced in chondritic constituents as well as in achondrites and silicate inclusions in iron meteorites. An example from **chondrule research**: Bulk INAA data on chondrules revealed that the highly diverse chemical compositions can be explained by mixing of a variety of precursors - refractory, moderately volatile and volatile lithophile and similar siderophile components. The refractory component was apparently of a nature similar to that of CAIs and related to olivine. However, it was not possible to identify it. From a suit of Allende chondrules from joint studies with Herbert Palme we selected some that spanned a range in bulk refractory element contents from about 1 to 10 x CI abundances. To our surprise the ion probe data (Fig. 2) showed that all glasses and matrices in these chondrules had high (~ 10 – 15 x CI) and almost identical refractory element abundances in all chondrules investigated – irrespective of the amount of matrix/glass! Three inescapable conclusions had to be drawn:

1) The long searched-for refractory component of chondrules is their matrix, crystalline or glassy,

2) The trace element abundances are volatility-dependent (see also Fig. 3), the liquid consequently of condensation origin, and

3) The variety of refractory element abundances in chondrules is determined by the mixing ratio of (olivine+pyroxene)/matrix. That way an unlimited number of chemical variety can be created – as is observed.

The next step was to find a carrier of the more volatile elements. Some of the moderately volatile elements, such as olivine/pyroxene-compatible Mn and Cr, were already known to follow Fe^{2+} in metasomatic invasions of components in chondrites [e.g., 4]. This way, also an unlimited compositional variety can be created – as is observed.

It was obvious to suspect that volatile elements were also added to chondrules and aggregates metasomatically – a process identified a long time ago [e.g., 4]. SIMS analysis of glasses in chondrules and aggregates showed that the trace element abundances in any glass of a given object are the same – except for the volatile elements (Fig. 3). Glass inclusions in olivine are commonly free of and the glassy matrix of a given object is very rich in alkalis. Obviously, the glass inclusion was protected by (and is in equilibrium with) the olivine but the matrix glass, which is now rich in alkalis and poor in Ca (out of equilibrium with olivine and pyroxene), must have had its chemical composition changed after the object solidified [5, 6]. Again, a metasomatic exchange of Ca for alkalis between the solid glass and the solar nebula is indicated and, again, unlimited compositional varieties can be created this way – as is observed.

Naturally, all these insights gained with the help of ions forced us to formulate a new, simple model for chondrule formation, which is capable of producing the unlimited multitude of chondrule/aggregate chemical compositions as we observe them [6, 7]. The "universal" liquid, however, not only is capable of producing most chondritic constituents but also plays a fundamental role in the formation of non-chondritic meteoritic rocks.

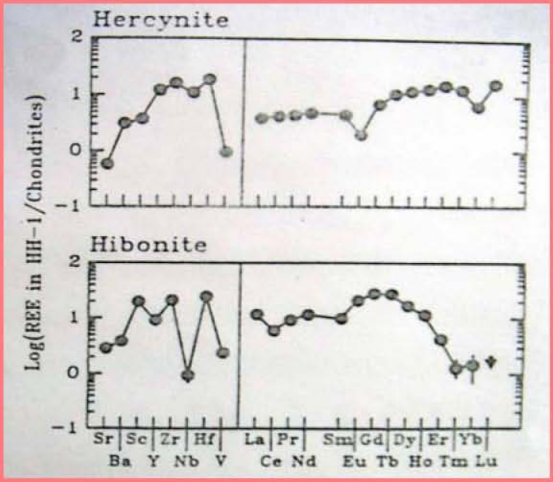

Fig. 1: Trace element abundances in hercynite and hibonite of a CAI from Lance (from [1]).

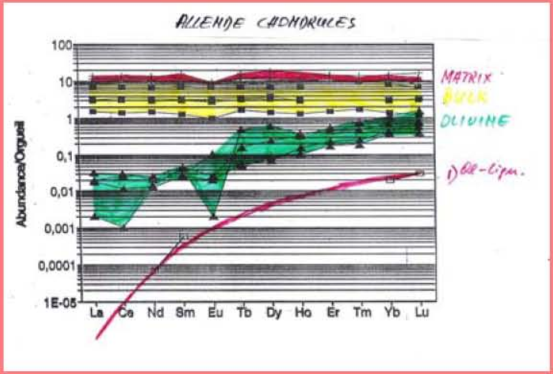

Fig. 2: CI-normalized abundances of REEs in bulk, matrix and olivine of a suit of Allende chondrules. Transparency presented at the LPSC in 1992 [3].

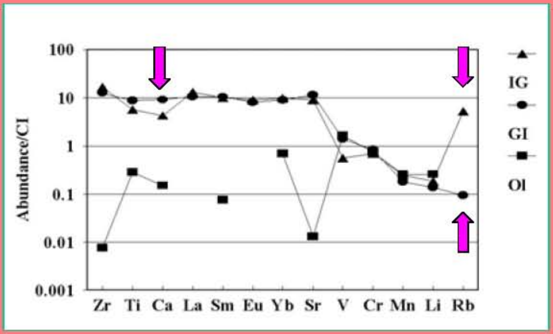

Fig. 3: Trace element abundances in interstitial glass (IG), a glass inclusion in olivine and in olivine of an aggregate from Kaba [from 5]. Note the depletion of the IG in Ca and enrichment in Rb.

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