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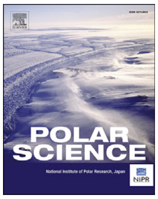

From supernova to Solar System: Few years only; first Solar System components apatite and spinel determined

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ABSTRACT

We show data for the very first years of our Solar System development after an interaction between undisturbed, cold interstellar dust and supernova type II explosion gases. All manual work was done in 1976–1982 as part of 3 theses works but fundamentally new data interpretation was reached within the last three years.

From the CI1 meteorite Orgueil, we are able to separate 1.4 per mill of material containing supernova related noble gases He, Ne and Ar as well as P.

We separate minerals using essentially density gradient centrifugation followed by stepwise heating noble gas analysis. Our procedure loses nearly no material and is in sharp contrast to the otherwise used dissolution of >99% of material to obtain single presolar grains (Anders and Zinner, 1993). Our method safeguards minerals considerably more fragile than SiC or TiC presolar grains, such as apatite, Mg-Al-spinel, graphite clusters and even apatite coated graphite clusters. We find graphite, apatite and Mg-Al-spinel containing highly anomalous noble gases. For the first time, apatite, containing anomalous Ar with an isotope ratio for $^{38}Ar/^{36}Ar$ of 0.35, twice the normal ratio, is reported. Such a ratio is produced by a 20 solar mass type II supernova in the C-O-Ne-burning shell. Unmatched pure Ne-E from ^{22}Na measured in the same samples sets the timeframe for this interaction to a maximum of only a few years.

1. Introduction

Meteorites are known to carry important information about the development of the wider region from where our Solar System originated. Large, cold dust areas contain mixtures of nucleosynthetic products from different sources such as supernovae, novae and Asymptotic Giant Branch (AGB) stars.

Work on Calcium Aluminum Inclusions (CAI) and chondrules stated minerals from CAI to be the first larger compounds formed, with ages of 4567.72 (±0.93) Myr, corresponding to the oldest objects reported until now (Connelly et al., 2012). Cameron and Truran (1977) have already proposed that the formation of the Solar System could have been triggered by a supernova explosion, and they assumed a presolar cloud in the form of a disk as progenitor structure of the Solar System. Recent publications from the ALMA observatory (Cieza et al., 2016) revealed dusty material as progenitors for Earth-like planets but also showed that the snow line even during outbursts is a maximum of 50 AU away from the central star, at 150 AU, still decreasing temperature is close to 30 K (Guidi et al., 2016). Further, Koo et al. (2013) report on near-infrared spectroscopic observations of the young SN remnant Cassiopeia A, that the abundance ratio of phosphorus to the major nucleosynthetic product iron (^{56}Fe) in SN material is up to 100 times the average ratio of the Milky Way, confirming that phosphorus is produced in supernova type II and ejected before mixing.

Separation of pure aggregates from useful meteorites is of utmost importance to gain information about temperature history and mineralogy based on the measured isotope compositions. In the invited review by Anders and Zinner (1993), the importance of noble gas analysis in discovering exotic matter and discussion of sources and processes is very well described. The author shows in detail that “undesirable minerals” are dissolved, leaving none but TiC or SiC single grains or graphite, all in all few per mill of the original material only. In their summary, they correctly state “the most pristine, unaltered interstellar grains provide little information on the early Solar System”. The method also applied by Busemann (1998) is summarized in Table A6 in the appendix. 48

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steps of 8 h or more are applied to meteorite material. Anders and Zinner (1993) in their paper falsely interpret (Jungck and Eberhardt, 1979) or completely neglect reviewed published papers (Eberhardt et al., 1979, 1981; Jungck and Eberhardt, 1985) which show the efficient even so very difficult separation method, the density gradient centrifugation (DGC). Their statement "non destructive, physical separations do not work well ..." is no reason not to apply them anyway. Unfortunately, their assumption led to 30 years of neglect of separating large numbers of typically μm– sized but pure mineral grains for high quality noble gas analysis by stepwise heating.

Noble gases have long been used and measurement techniques developed to highest level, as shown in the Bernese Solar Wind Sail (Geiss et al., 1972) or lunar sample analysis (Bochsler et al., 1969; Eberhardt, 1974; Eugster et al., 1975, 1984). For Ne, a three stable isotope noble gas, the use of 3-isotope plots gives significant information on its sources - Solar Wind, Ne-A, Ne-B, Ne-C, Earth atmosphere and cosmic ray produced Ne_c. Plotting the isotope ratios $^{20}Ne/^{22}Ne$ versus $^{21}Ne/^{22}Ne$, all measured Ne isotope ratios, until 1969, fit into a triangle of Ne-D, Ne-A and GCR Ne-spallation and could be explained as mixture of these 3 end members. (Fig. 1 from Eberhardt, 1978). Note that GCR Ne-spallation is represented by an area, not a point, representing different elemental composition, different particle impact as well as different irradiation age.

Black and Pepin (1969) discovered trapped Ne in Orgueil (CI1) with a ratio of $^{20}Ne/^{22}Ne = 3.4–4.8$, far outside the regular triangle, using stepwise heating technique which had been used regularly for Ar-Ar age determinations until then. Subsequently a hunt for even more extreme ratios was triggered, demanding optimal separation and description of the carrier phase for the anomalous Ne. In the end, virtually pure ^{22}Ne, originating from ^{22}Na (2.6y half-life) could be separated and measured (Jungck and Eberhardt, 1979). After a successful separation of Ne-E-bearing phases in Orgueil, Eberhardt (1974), *nota bene* in Chicago, using mild basic chemical treatment followed by normal gravity density separation in liquids, it was clear to him, that techniques retaining most of the valuable meteorite material were possible. After serious discussion, this led to the separation technique using strong centrifugal forces produced in liquid density gradients, for details see sample preparation (section 2.4). Around 95% of the original material remains unaltered and separated into minerals of uniform densities. The extreme manual skills required for high quality separations were only applied by Niederer (1978) and Jungck (1982) despite the outstanding results (Eberhardt et al., 1981).

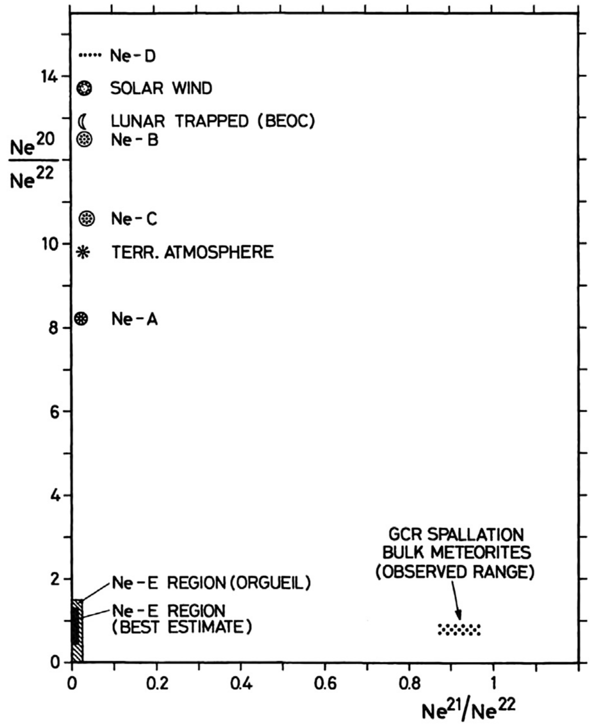

Fig. 1. Isotopic composition of different meteoritic neon components. Solar Wind: Geiss et al. (1972); terrestrial atmosphere: Eberhardt et al. (1965); Ne-A: Pepin (1967); Ne-B, Ne-C, Ne-D: Black (1972); Ne-E region: this paper; GCR spallation on bulk meteorites: Nyquist et al. (1973). The $^{21}Ne/^{22}Ne$ ratio of Ne-D is not known. The range shown for spallation $^{20}Ne/^{22}Ne$ is our estimate.

The current paper re-investigates our published results from 1976 to 1986, but about four years ago, we discovered new insights about isotope sources, formation processes and thermal history not only of the separated minerals, but also the environment they were formed in, insights that required a new publication. In particular the currently accepted time frame of <200 Myr for mixing interstellar grains into a rotating presolar disk will be questioned. We instead find an interaction of supernova gases with cold, non-rotating interstellar dust within a few years to be the more accurate model for the initial time of our Solar System. Theoretical models on supernova evolution were developed since 1981. Of particular interest to our measurements was the consideration of noble gas isotopic ratios related to different shells from advanced nuclear burning stages (Clayton, 1981). In the appendix of the invited review paper by Anders and Zinner (1993), a survey "nucleosynthesis and stellar evolution" is given. Based on our measurements, we contest the statement by Alexander (1993), that ^{22}Ne and ^{4}He, hence also rare gases from our samples, originate from the shell of AGB stars. The measurements published earlier, but also the new interpretations, clearly disagree with this statement.

We restrict data and interpretations to noble gases He, Ne and Ar in Orgueil, other measurements on He, Ne, Ar, Kr, Xe in Dimmitt, St. Séverin, Murchison and Cold Bokkeveld as well as further technical details may be published later on. However findings of relevance to our discussions from these meteorites are already used in the current paper. As a result of our investigation, we enlarge the suffix of the noble gases by "SN" denoting supernova produced similar to Ne_c for cosmogenic produced neon. We prove that Ne-E(h) and Ne-E(l) result from differences of their carrier, not the nucleosynthetic source. We now assume ^{22}Na from a SN being the source for Ne-E, from now on denoted Ne_{SN}. In a similar way, we designate the excess components as He_{SN}, Ne_{SN} and Ar_{SN}.

We will seek more adequate answers about sources, structure, incorporation effects, as well as thermal history, within the very first period of the Solar System.

2. Analytical procedures

2.1. Mass spectrometry

The noble gas analysis was performed at the facility developed in 1970 for lunar sample analysis. (Schwarzmüller, 1970). Samples wrapped in Al-foil were filled into a 4g Mo crucible that could be heated by induction with up to 25 kW RF-power to temperatures up to 2100 °C. The temperature was measured using optical pyrometers to less than 10 °C precision. Noble gases were purified and directly connected to two mass spectrometers: for He and Ne to a 90° magnetic sector type and for Ar to a 2 × 90° tandem instrument (Schwarzmüller, 1970). Both mass-spectrometers had magnetic field control for predefined peak switching. All measurements used a faraday-cup detector and Cary preamplifier, 10^{11}Ohms resistor. A multiplier detector was available and used for blank measurements. Eberhardt (1978) reported blank values for ^{20}Ne of

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