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The Achievements of the RockStar Group (Perugia) on Astrophysical Modelling and Pallasite Geochemistry

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Abstract: In the present work we summarize the first achievements of the RockStar Group of the Department of Physics and Geology (at the University of Perugia, Italy), which is made of a strict collaboration between Physicists and Geologists on astrophysical and planetological studies. The RockStar Group acts on two research lines: (i) astrophysical modeling and (ii) mineralogical and geochemical studies of meteorites. In the first part of the article we review the recent results concerning the development of theoretical modeling of nucleosynthesis and mixing process in asymptotic giant branch. In the second part we report (1) the catalog of the Meteorite collection of University of Perugia and (2) major and trace elements mapping, performed through EPMA and LA-ICP-MS, of the Mineo pallasite, a unique sample hosted by the collection. The new data constrain the Mineo meteorite among the Main Group Pallasites and support the hypothesis of the "early giant impact" formation.

Keywords: Mineo; EPMA; LA-ICP-MS; chemical mapping

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1. Introduction

Coupling the expertise from different scientific fields is nowadays mandatory to achieve new milestones, add knowledge and validate models. Astrophysical modeling takes significant advantage of geochemical investigations on meteorites [1–3], since they store, like a coffer, information about the early Solar System and its evolution [4,5]. Moreover, geochemical and structural investigations in minerals, crystals, and quasi-crystals can provide the basis for modeling the formation and the physical evolution of meteorites and planetary bodies [6–10].

In order to face cross-disciplines topics on astrophysical and planetological studies, a strict collaboration between Physicists and Geologists of the Department of Physics and Geology of the University of Perugia (Italy) has been set up naming this informal group RockStar Group.

In the present manuscript, we describe main activities and results of the RockStar Group, both in astrophysical modelling and meteorite classification, with particular focus on new geochemical data of the Mineo pallasite, a unique sample re-discovered during the initial stages of RockStar Group activities.

2. Roadmap of the RockStar Group

The RockStar Group started its activities in 2014, a few months after the founding of the Department of Physics and Geology of the University of Perugia (Italy) in 2013, when the previous Physics and Earth Sciences Departments merged, joining their well-established scientific traditions. The group has been initiated by Maurizio Busso (University of Perugia) and it has beneficiated by Maurizio's mentorship for the first seven years. The first two years of activity have been directly funded by the University of Perugia, then the activities of the RockStar Group continued within the INFN (National Institute of Nuclear Physics) project named ERNA2.

The activities of the RockStar Group are mainly focused on two research topics: (i) the development of theoretical modeling of nucleosynthesis and mixing processes in asymptotic giant branch (AGB) and (ii) the classification and the mineralogical-geochemical study of meteorites.

3. Using Geochemical Data to Constraint Astrophysical Modeling

Astronomers have traditionally studied the stars through the inspection of their electromagnetic radiation emissions. However, since the mid-1980s, the analysis of primordial meteorites and presolar grains therein contained has paved the way for a new approach to studying the stars. These grains can be recovered within undifferentiated meteorites after chemical and physical separation from the hosting material [11] and preserve the chemical and isotopic composition of the stellar environments where they condensed, thus providing robust constraints on theoretical models of nucleosynthesis (see, e.g., [12]).

The isotopic compositions of presolar grains are determined in laboratories all over the world, e.g., [13–17]. A convenient source for accessing the data for a wide range of isotopic compositions and grain types is the "Presolar Grain Database" (PGD) maintained by the Department of Physics of Washington University in St. Louis [18,19]. It is a collection of spreadsheets containing the isotope data on presolar grains (SiC, Graphite, Oxides, and Silicates; [18,19]). As an example, the PGD for Mainstream SiC contains ~20,000 isotopic ratio measurements for Si and C, mainly determined by Nanoscale Secondary Ion Mass Spectrometry (NanoSims, e.g., [17]), and a few identifications of trace heavy elements, analyzed by Resonance Ionization Mass Spectrometry (RIMS, e.g., [20,21]). The majority of those grains (>90%), known as mainstream (MS) SiC grains, have been shown to provide crucial knowledge about the nucleosynthesis of the progenitor stars with higher accuracy ($\lesssim$10%) than direct stellar observations (typically about a factor of two). Their typical C, N, and Si isotope ratios, as well as evidence of s-elements, i.e., elements heavier than iron made through the slow (s) neutron capture process (e.g., [22]) detected in a selection of them, indicate that they originated in asymptotic giant branch (AGB) stars (see [23] for a review). In this respect, theoretical modeling of nucleosynthesis and mixing processes in AGB stars can be empirically constrained using presolar MS SiC grains data (e.g., [24–28]).

A fundamental aspect of the RockStar project concerns providing the necessary theoretical support to future meteoritic analyses. In this regard, great attention has been paid to developing state-of-the-art nucleosynthesis models of low-mass ($M < 3\ M_\odot$) AGB stars. Since the seminal work of Busso et al. (2007) [29], the nuclear astrophysics group of Perugia has been deeply involved in theorizing a new paradigm in which the process occurring in those stars is driven by magnetohydrodynamic (MHD) phenomena [30]. Such efforts have recently culminated in a series of works showing that the proposed MHD scenario for the formation of the main neutron source in AGB stars, the so-called ^{13}C pocket, can account for several observational constraints (e.g., [27]) and, in particular, for the isotopic abundance ratios of s-elements in presolar MS SiC grains of stellar origin [3,26,28].

Previous comparisons of s-process computations with isotopic ratios of s-elements in individual presolar SiC grains showed that the latter can be safely used to constrain the extension and the shape of the ^{13}C pocket [24], but not the stellar metallicities of their parent AGB stars [25]. In this regard, the Si content of MS grains suggests that their progenitor star had either near-solar or slightly super-solar metallicity [31,32]; whereas, integrated approaches combining chemical and chemodynamical models of the Galaxy with dust yields from AGB models, revealed that the majority of presolar SiC grains come from AGB stars with $M \sim 2\ M_\odot$ and close-to-solar metallicity [33,34]. In Figure 1, we compare the latest Perugia model predictions [28] with available laboratory measurements of selected isotopic ratios for Sr, Zr, and Ba in presolar SiC grains. For the aforementioned reasons, the comparison is restricted to stellar models of 2 $M_\odot$ and with metallicity [Fe/H] [1] between −0.15 and +0.1. In general, model predictions and grain data match fairly well, with the former reproducing almost all of the data spread. Thus, the proposed MHD-induced mechanism for driving mixing and neutron-capture processes in AGB stars offers a solid astrophysical interpretation for available s-elements isotopic ratios in presolar SiC grains from those stars.

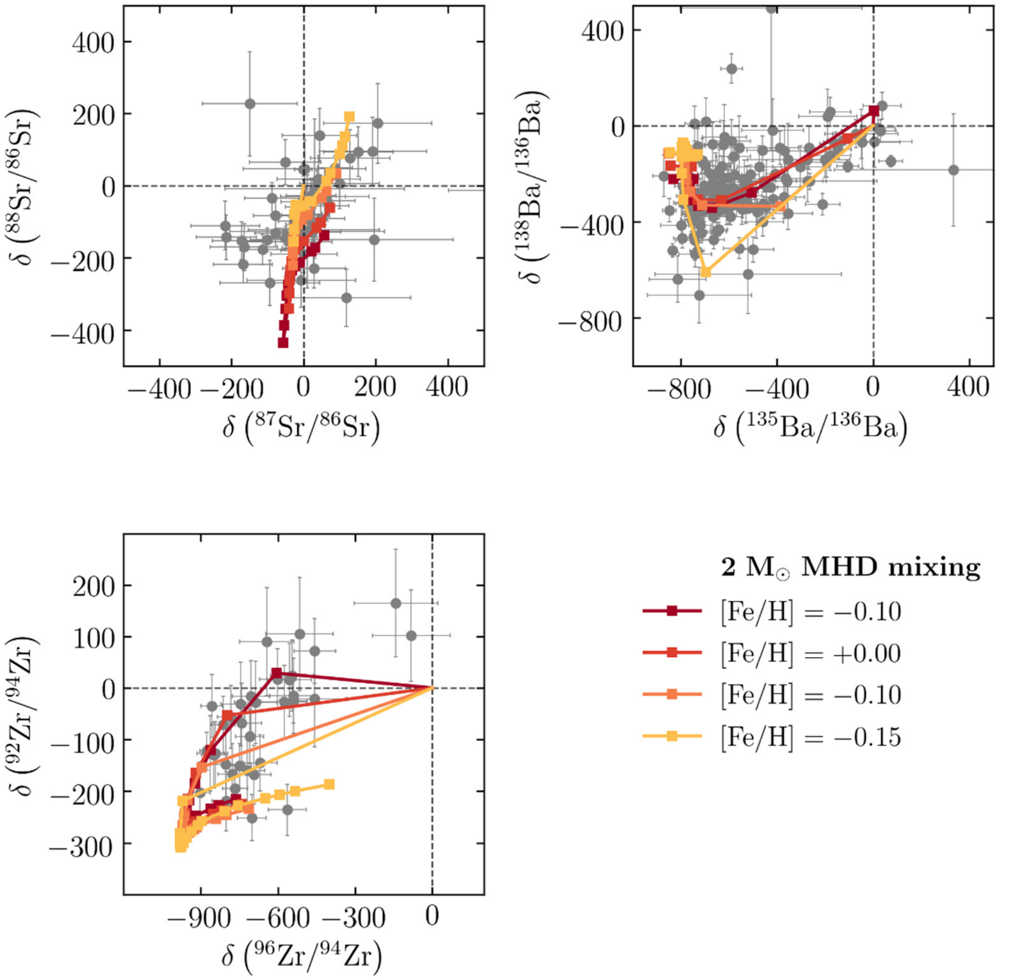

Figure 1. Comparison between s-process models for AGB stars and presolar MS SiC grain data for Sr, Ba, and Zr. Isotopic ratios are expressed as part-per-mil deviations (δ) from the terrestrial value. Models are from Ref. [28] and refer to 2 $M_\odot$ AGB stars at different metallicities, where magneto-hydrodynamic (MHD) processes induce the formation of the ^{13}C pocket. Abundances are computed in stellar winds by considering 5% of mixing due to C-rich material transported to the envelope by magnetic blobs (see Ref. [28] for more details). Grain data are from the PDG database [19]. The picture is modified after Palmerini et al. (2021) [28].

Nonetheless, since the multielement and multi-isotope composition is known only for a small subset of the available meteoritic samples, the comparison is somewhat limited. For example, the PGD reports 18 samples where Ba and Zr isotopes are both determined. On the one hand, the Rockstar project aims to perform new SiC grain measurements to study the correlation between those particular isotope ratios that are, at present, poorly constrained and to test theoretical predictions against them. On the other hand, it also points toward understanding the cosmic origin of different classes of meteorites, containing metal-silicate aggregates of various species, as carbonaceous chondrites and pallasites (see Section 5).

4. The Meteorite Collection at the Department of Physics and Geology in Perugia and the Discovery of a Unique Sample

The second research line is the mineralogical and geochemical study of the meteorites available in the collection of the Department of Physics and Geology of Perugia University (Italy). The main goal of this activity is the classification of the samples, formerly classified according to the traditional scheme (stony meteorites, iron meteorites and stony irons), according to the recent classification scheme based on their degree of differentiation [35].

The Meteorite collection of University of Perugia was instituted in 1964 by the Italian Center for Meteorite Studies, in the Mineralogical Institute of University of Perugia (Italy). The collection started with only five samples, but the number of specimens rapidly increased reaching a total of 30 hand-size samples and numerous thin sections in December 1969, when the Mineralogical Institute of University of Perugia (Italy) published a catalog of the collection [36]. The catalog contains the list of samples and the picture, description and references of each sample (Figure 2).

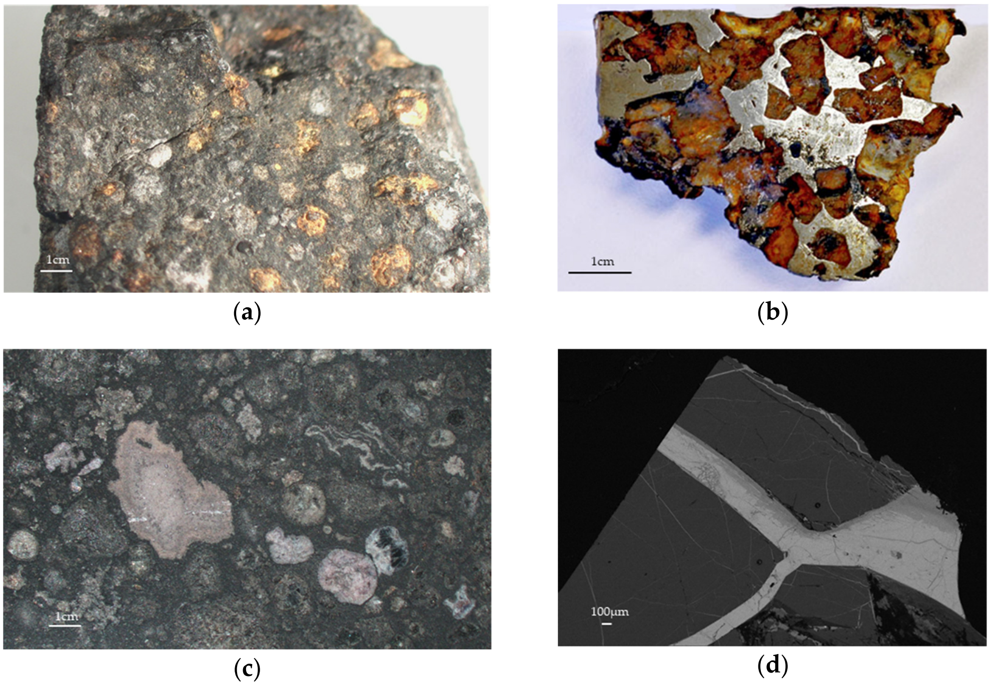

Figure 2. Images of some specimens of the Meteorite collection of the University of Perugia (Italy) at different scales. (**a**) Vigarano; (**b**) Mineo; (**c**) Allende (images acquired by optical microscope); (**d**) Mineo (image acquired by EPMA).

During the following years, the collection has been enriched with several new specimens, but the original catalog has never been updated until 2014, when the Department of Physics and Geology of University of Perugia (Italy) started updating the catalog.

Nowadays, the collection hosts a total of 49 specimens of meteorites, including 29 chondrites, 11 achondrites, 6 primitive achondrites and 3 iron meteorite specimens not attributable to a single category due to the lack of information (Table A1). Furthermore, the collection includes numerous tektites, impactites, and metallic spherules.

On the total of available chondrite, 26 are ordinary. Among the ordinary chondrites, 11 belong to the H type, 13 are L-type chondrites and the remaining ones are of LL and L/LL type. Also, the collection stores 3 samples of world-famous carbonaceous chondrites: two samples of Allende and one of Vigarano [37,38].

During the update of the catalog in 2014, we discovered a piece of the rare Mineo pallasite. In detail, the Mineo pallasite was acquired by the Department of Earth Sciences of University of Perugia (Italy) in 1965 and it was roughly described by Baldanza (1965) [39] and Nagata (1979) [40]. At the present, the sample hosted by University of Perugia (Italy) is the only known sample available in public collections [41]. This sample deserve further studies since: (a) is one of only the two collected in Italy; (b) it is still poorly investigated.

In detail, we aim to provide new mineralogical and geochemical data of some poorly studied meteorites in order to infer some hypothesis about their origin. Within this framework, the main results concerned the Mineo pallasite, a rare pallasite whose only sample available in public collection is hosted by University of Perugia. This pallasite was never studied before 2018, when Zucchini et al. (2018) [41] reported a detailed description of the mineralogical features and some geochemical data of the specimen stored at the University of Perugia (Italy). After this first study, new geochemical data have been collected in the following years and will be presented in this article.

5. The Mineo Pallasite: A Unique Sample

Pallasites are stony-iron meteorites composed of silicate mineral phases, i.e., olivine always present and, in some cases, pyroxene, hosted in a metallic (Fe, Ni) groundmass [35,42]. Their origin is still debated with hypotheses ranging from the "early giant impact" proposed by Yang et al. (2010) [43] to the result of ferrovolcanic eruptions [44]. In the first scenario, Main Group (MG) pallasites would have been formed from an impact that mixed residual Ir-poor molten metallic Fe-Ni from the outermost part of a IIIAB-like core with olivine mantle fragment [44]. If the pallasite formation was related to ferromagmatism, as suggested by Johnson et al. 2019 [44], then pallasites may be intrusions of evolved core magmas into an olivine-rich mantle body [44].

The classification of Pallasites defines four different groups: (1) the Main Group pallasites (PMG), (2) the Eagle Station grouplet (ES), (3) pyroxene pallasites, and (4) the Milton ungrouped pallasite [35].

The Mineo pallasite is one of only the two collected in Italy [41] and belongs to the only four witnessed pallasite falls worldwide [45]. The Mineo fall occurred on 3 May 1826, when a bright meteor was observed over Sicily and a fall occurred near the town of Mineo [41]. To our knowledge, the sole portion (i.e., 42 g) of the Mineo meteorite that is of public access, belongs to the Department of Physics and Geology of University of Perugia (Italy).

Despite its uniqueness, the Mineo pallasite was not extensively studied before 2018, when Zucchini et al. (2018) [41] reported a detailed description of the mineralogical features and some geochemical data of the Mineo sample stored at the University of Perugia (Italy).

Zucchini et al. (2018) [41] observed an olivine-metallic portion of 65–35% by volume, respectively. The olivine composition is in the range Fo_{88}-Fo_{84}, and the metal phase is essentially composed of iron (Ni abundance of 5 ± 1 wt%, on average), taenite (Ni of ~20 wt%), barringerite, and schreibersite. Trace element chemical composition of the Mineo (Fe, Ni) metal shows enrichments in Ir, Re, and Os [41]. The distribution of the platinum group elements follows the same qualitative behavior of the IIIAB iron meteorites, which formed during the later fractional crystallization stages [41,46]. This evidence agrees with the well-documented link between pallasites and fractionated IIIAB irons [46]. In the Ga-Ge diagram (Figure 3), often used to discriminate between Eagle Station (ES) and Main Group (MG) pallasites [47], the Mineo pallasite plots in the MG field. As a consequence, the results reported by Zucchini et al. (2018) [41] allowed a preliminary classification of the Mineo meteorite to the PMG. Note that the olivine phase shows a compositional variability in terms of Fe and trace elements, to an extent that is known from only one other pallasite, Glorieta Mountain [41]. According to Zucchini et al. (2018) [41], most of the features observed in the Mineo pallasite are consistent with the "early giant impact", theory proposed by Yang et al. (2010) [43]. Alternatively, the observed variations in olivine compositions might also derive from the crystallization in two differentiated parent bodies [41] or be the result of ferrovolcanic eruptions [44]. However, these hypotheses need to be verified by further analyses, such as the isotopic composition of the olivines, to discriminate their origin either from one or more parent bodies [41].

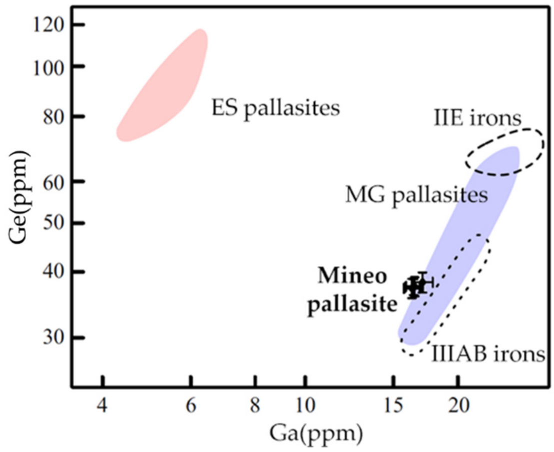

Figure 3. Logarithmic Ga-Ge plot where Eagle Station (ES, red) and Main Group (MG, blue) pallasite fields are shown together with meteorite fields of IIIAB irons (dotted line) and IIE irons (segmented line). The Mineo data are in black (after Scott 1977 [47]). The picture is modified from Zucchini et al. (2018) [41]. (Color figure can be viewed at wileyonlinelibrary.com).

Besides the mechanism of pallasite formation, several studies focused on the origin of olivines and two main alternative hypotheses were proposed [48–51]. One possible origin is that they are cumulates from an originally molten asteroid and a second possibility is that they have a restitic origin. A third possibility is that they are cumulus grains plus a trapped melt component, but the modal pyroxene content is generally too low to support this hypothesis [48].

6. New Determinations on the Mineo Pallasite

In the following, we present new Electron Probe Micro Analysis (EPMA) and Laser Ablation-Inductively Coupled Plasma-Mass Spectrometry (LA-ICP-MS) data to characterize further the Mineo pallasite. The main aims are to examine the compositional variability highlighted by Zucchini et al. 2018 [41] through the elemental and trace element mapping of a selected olivine crystal within the Mineo pallasite and to evaluate the implications of the revealed geochemical signature for the origin of pallasites.

6.1. Methods

6.1.1. EPMA

The elemental distributions of Mg, Si, Fe, Ni within the Mineo pallasite were performed with EPMA-WDS JEOL 8200 Super Probe with 5 WDS (wavelength dispersive spectrometer) channels and one EDS (energy dispersive spectrometer) channel at the Electron Microprobe Laboratory of the Earth Science Department "Ardito Desio" (University of Milan, Italy). The resulting maps were reported in Figure 4. Maps were acquired (i) in WDS, with exception of Ni (acquired in EDS); (ii) as semi-quantitative, i.e., the color-scale is relative to the counts of each element; (iii) with acquisition time for each pixel of 30 ms; (iv) with a voltage of 15 kV.

6.1.2. LA-ICP-MS

Olivines were imaged following the line rastering technique proposed by Ubide et al. (2015) [52] to produce multi-elemental crystal maps. The analyses were performed by LA-ICP-MS at the Petro-Volcanology Research Group (PVRG) facility, Department of Physics and Geology (Perugia), using a Teledyne Photon Machine G2 laser system coupled to a Thermo Fisher Scientific iCAP-Q ICP-MS. Helium was used as carrier gas with Ar and N_2 added after the ablation cell to avoid plasma destabilization and enhance the instrumental sensitivity. We used a spot size, scan speed, repetition rate, and fluence of 10 µm, 6 µm/s, and 15 Hz, 3.5 J/cm^2, respectively. The NIST SRM610 [53] and the USGS BCR2G [53] have been used as calibrator and quality control, respectively. Under the reported analytical conditions, precision and accuracy are typically better than 10%. Crystal maps were finally produced using the Iolite [54]. LA-ICP-MS compositional maps in Figure 5.

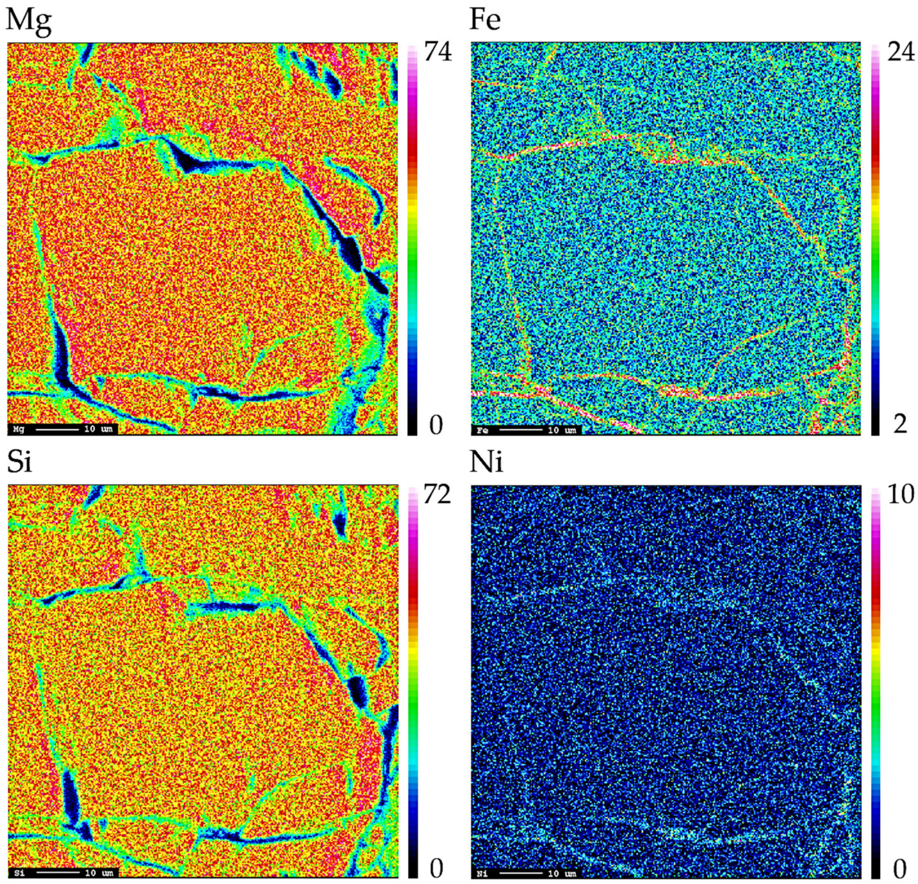

Figure 4. Quantitative EPMA distribution maps of Mg, Fe, Si, Ni in a selected olivine crystal within the Mineo pallasite. The color-scale is relative to the counts of each element.

6.2. Results and Discussion

EPMA element distribution maps (Figure 4) highlight quite fragmental olivines with not sharp crystal-metal rims. Fe and Mg distributions are relatively homogeneous within a single olivine grain. This allows to conclude that the Fe compositional variability observed in Zucchini et al. (2018) [41] is not the result of Fe chemical zoning within single olivine grains/crystals; on the contrary, it can be attributed to different grains/crystals in the Mineo pallasite. Along olivine rims, Fe and Mg show complex distributions, with zones enriched and depleted in Mg and Si, showing an inverse correlation to Fe and Ni. Both Mg and Si ranges between 0 and 70 counts per second, reaching higher values within olivines and lower ones in correspondence with the metallic phases. Fe and Ni appear correlated and constitute the metallic phase that surrounds olivines, but Fe ranges between 2 and 24 counts per second while Ni is from 0 to 10 counts per second.

LA-ICP-MS trace element distribution maps within olivine crystals (Figure 5) reveal a concentration gradient in Cr, with alternating enriched and depleted bands, attributable to an oscillatory zoning pattern. The concentration gradient in Ti is correlated with that of Cr. The trace element maps of Mineo olivine also highlight the presence of veinlets or cracks enriched in P, Fe and Ni (10–20 µm in width), which cross the entire analyzed area. In particular, Ni is extremely enriched in the P-rich veinlets, showing value up to 50×10^3 ppm. In contrast, the distributions of Cr and Ti appear to be independent from the P-rich veinlets. The origin of this feature may be either linked to shock [55], associated with partial melting [56] or could be related to terrestrial weathering [57]. The Cr concentration of Mineo olivines estimated by Zucchini et al. (2018) [41] ranges between 161 and 544 ppm and is, in average, 321 ± 173 ppm. Figure 6 shows that the Cr content within Mineo olivines is slightly higher than the Cr concentration in pallasitic olivines from literature (87–237 ppm, [57]) but is below that found on Mars and Moon [58] and the Cr/Mn ratio is in the range, or slightly higher, than other PMG. Furthermore, the Cr to Al molar ratio in the Mineo olivine is close to 1 (average = 1.4), in agreement with those estimated by Chernonozhkin et al. (2021) [57] for the majority of the analyzed pallasites.

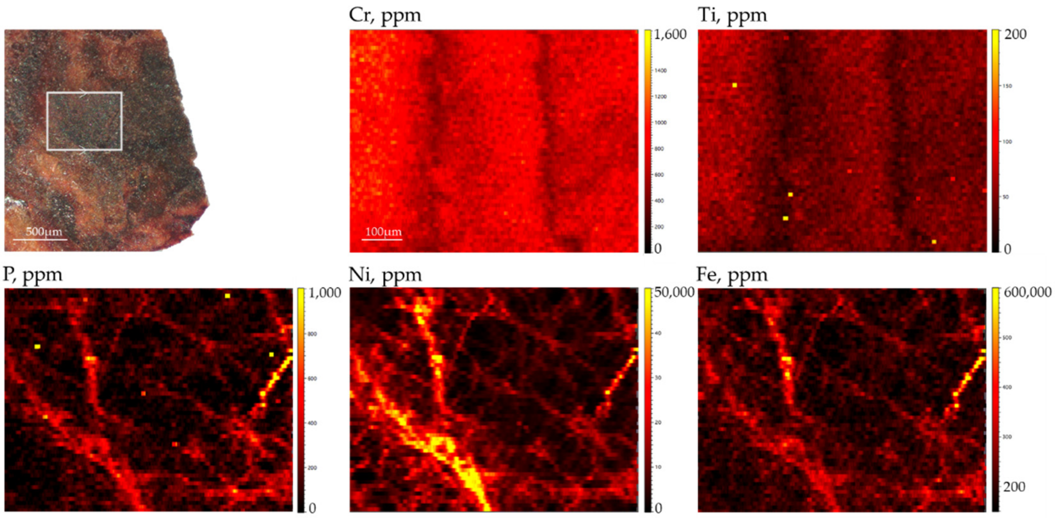

Figure 5. Quantitative LA-ICP-MS distribution maps of Cr, Ti, P, Ni, Fe within an olivine crystal of the Mineo pallasite. The image on the top left indicates the area where the maps were acquired and the direction of the acquisition. The color-scale is relative to the parts per million of each element.

To start assessing which scenario is most likely for the origin of olivines hosted in the Mineo pallasite, we compare the Fe/Mg versus Fe/Mn plot of Mineo olivines with those of other PMG (Figure 7). Mineo values fall in the same trend defined by Chernonozhkin et al. (2021) [57], suggesting a common history. Also, Cr content of olivines in the Mineo pallasite is in the same range of PMG. Finally, Mineo pallasite share the evidence of oscillatory Cr zoning with the Imilac pallasite. The cause of this oscillatory zoning is largely debated [57,59]. McKibbin et al. (2013) [59] suggest that the oscillatory zoning may be a superimposed feature and attributes pallasite olivines to a restitic origin, while Chernonozhkin et al. (2021) [57] provide multiple explanations, all related to magmatic processes, concluding that the existence of oscillatory zoning within an olivine leads to exclude the formation of the crystal as a mantle restite. As a conclusion, our data support a similar history of the Mineo pallasite with the Esquel, Seymchan, Fukang and CMS 040071 pallasites. Considering the model of Chernonozhkin [57], based on a chondritic starting Mn/Mg composition, the Mineo olivines' origin may be attributed either to a fractional crystallization or accumulation. However, Mittlefehldt et al. (1999) [48] calculations show that a simple cumulus origin is implausible. The explanation of the Cr oscillatory zoning requires further investigations and the petrologic evolution of olivines remains matter of debate.

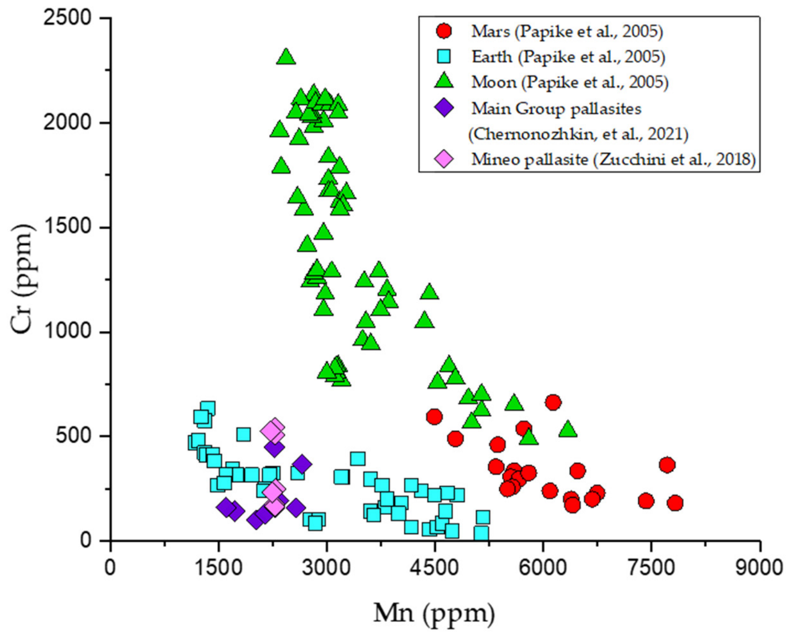

Figure 6. Concentration of Cr (ppm) and Mn (ppm) in olivine from planetary basalts, compared with the concentration found within 8 PMG olivines [57] and Mineo pallasite olivines [41]. Modified after Papike et al. (2005) [58].

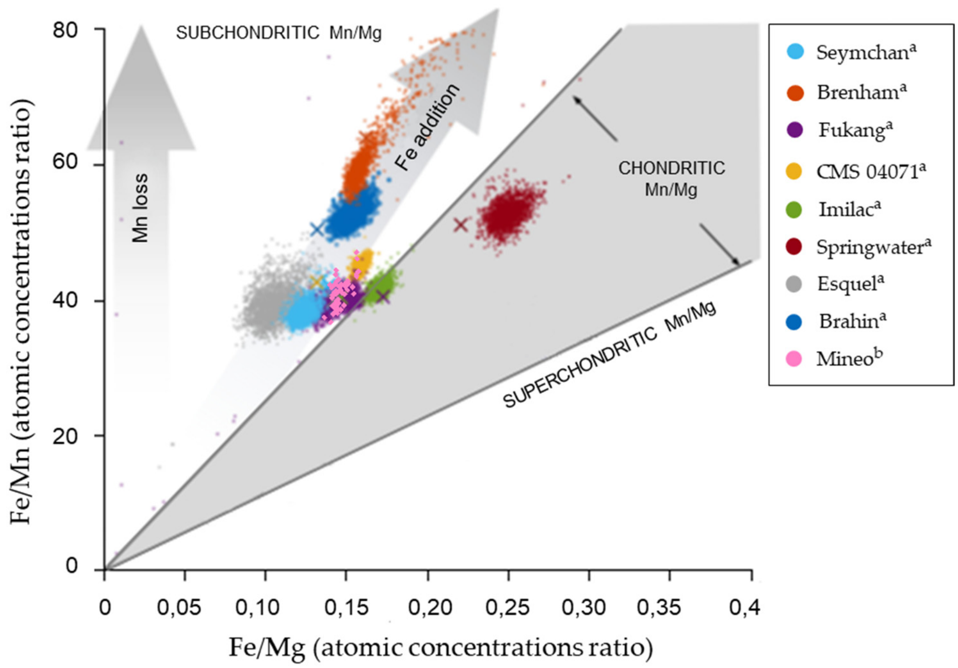

Figure 7. Fe/Mg-Fe/Mn pallasite olivines plot. The picture is modified after Chernonozhkin et al. 2021. Chernonozhkin et al. 2021 [57] [a] Zucchini et al. 2018 [41] [b].

7. Conclusions

In the present work, the preliminary achievements of the RockStar Group of the Department of Physics and Geology (University of Perugia, Italy) can be summarized as follow:

1. Astrophysical modelling. In recent years, an extended study on the nature of the mixing processes in AGB stars was pursued by the astrophysics group of Perugia led by Maurizio Busso. Latest nucleosynthesis models considering the activation of

the ^{13}C neutron source in AGB stars as a by-product of magnetically-induced mixing episodes were shown to explain several observational constraints on s-processing. In particular, magnetic models for low-mass stars with close-to-solar metallicity can reproduce the peculiar isotopic ratios of trace heavy elements measured in presolar SiC coming from ancient AGB stars.

2. Geochemical mapping of Mineo pallasites. The results from Zucchini et al. (2018) [41] allowed a preliminary classification of the Mineo meteorite to the PMG and showed a Fe compositional variability in olivines. In the present work, trace element distribution maps allowed to better constrain the geochemical variability showing that it can be attributed to different olivine grains/crystals and not to the chemical zonation within them. In fact, major element distribution maps highlight a relatively homogeneous distribution of Fe and Mg within olivine crystals and a more complex pattern along olivine rims, with zones enriched and depleted in Mg and Si, which show an inverse correlation to Fe and Ni. These characteristics confirm that Mineo belongs to the PMG and support the hypothesis of "early giant impact" formation theorized by Yang et al. 2010 [43]. Furthermore, trace element maps highlight also an oscillatory zoning pattern of Cr, but this behavior is not explained by a single model of olivine formation and further studies are needed in order to shed a light in the petrological evolution of pallasite olivines.
3. The meteorite collection. The specimens hosted by the Meteorite collection of the Department of Physics and Geology of Perugia University (Italy) have been classified according to the hierarchy introduced by Weisberg et al. (2006) [35].

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. List of meteorite specimens hosted by the Meteorite collection of University of Perugia (Italy), classified following the scheme proposed by Weisberg et al. (2006) [35].

Meteorite Specimens	Traditional Classification	Modern Classification [35]								
Name	**Category**	**Category**	**Class**	**Clan**	**Group**	**Petrologic Type**	**Weight (g)**	**Fall**	**Find**	**References**
Albareto	chondrite	Chondrites	Ordinary	H-L-LL	L/LL	4	7.47	1776		[60]
Allende	chondrite	Chondrites	Carbonaceou	CV-CK	CV	3	44.87	1969		[61]
Allende	chondrite	Chondrites	Carbonaceou	CV-CK	CV	3	93.97	1969		[61]
Armel	chondrite	Chondrites	Ordinary	H-L-LL	L	5	50.9	-	1967	[62]
Ashmore	chondrite	Chondrites	Ordinary	H-L-LL	H	5	104.1	-	1969	[63]
Bledsoe	chondrite	Chondrites	Ordinary	H-L-LL	H	4	55.1	-	1970	[64]
Bondoc	mesosiderite	Achondrites			MES		30.2	-	1956	[65]
Bondoc	mesosiderite	Achondrites			MES		46.4	-	1956	[65]
Boxhole	octahedrite	Achondrites			IIIAB		61.9	-	1937	[66]
Boxhole	octahedrite	Achondrites			IIIAB		49.2	-	1937	[66]
Brenham	pallasite	Achondrites			MG PAL		193	-	1882	[67]
Calliham	chondrite	Chondrites	Ordinary	H-L-LL	L	6	48.6	-	1958	[68]
Canyon diablo	octahedrite	Primitive Achondrites		WIN-IAB-IIICD	IAB		118	-	1891	[69]
Canyon diablo	octahedrite	Primitive Achondrites		WIN-IAB-IIICD	IAB		104	-	1891	[69]
Canyon diablo	octahedrite	Primitive Achondrites		WIN-IAB-IIICD	IAB		135	-	1891	[69]

Table A1. *Cont.*

Meteorite Specimens	Traditional Classification	Modern Classification [35]									
Name	**Category**	**Category**	**Class**	**Clan**	**Group**	**Petrologic Type**	**Weight (g)**	**Fall**	**Find**	**References**
Clovis (no 2)	chondrite	Chondrites	Ordinary	H-L-LL	L	6	37.9	-	1963	[70]
Densmore (1879)	chondrite	Chondrites	Ordinary	H-L-LL	L	6	96.4	-	1879	[71]
Dimmitt	chondrite	Chondrites	Ordinary	H-L-LL	H	3.7	48	-	1942	[72]
Edmonson (a)	chondrite	Chondrites	Ordinary	H-L-LL	L	6	35.5	-	1955	[73]
Ergheo	chondrite	Chondrites	Ordinary	H-L-LL	L	5	-	1889		[74]
Etter	chondrite	Chondrites	Ordinary	H-L-LL	L	5	48.4	-	1965	[66]
Gibeon	octahedrite	Achondrites			IVA		82.2	-	1836	[75]
Gruver	chondrite	Chondrites	Ordinary	H-L-LL	H	4	63.8	-	1934	[76]
Henbury	octahedrite	Achondrites			IIIAB		503	-	1931	[77]
Hoba	ataxite	Achondrites			IVB		16.2	-	1920	[78]
Lakewood	chondrite	Chondrites	Ordinary	H-L-LL	L	6	35	-	1955	[79]
Landes	octahedrite	Primitive Achondrites		WIN-IAB-IIICD	IAB		81.49	-	1930	[64]
Little River (b)	chondrite	Chondrites	Ordinary	H-L-LL	H	4/5	36.3	-	1965	[80]
Messina	chondrite	Chondrites	Ordinary	H-L-LL	L	5	16	16/07/19		[81]
Mineo	pallasite	Achondrites			MG PAL		42	03/05/18		[41]
Odessa	octahedrite	Primitive Achondrites		WIN-IAB-IIICD	IAB		452.52	-		[82]
Otasawian	octahedrite				doubtful Iron		634	-	1907	[83]
Otasawian	octahedrite				doubtful Iron		803	-	1907	[83]
Patti	octahedrite						12	1922		[84]
Picacho	octahedrite				IIIAB		175.4	-	1952	[85]
Plains	chondrite	Chondrites	Ordinary	H-L-LL	H	5	34.3	-	1964	[62]
Plains	chondrite	Chondrites	Ordinary	H-L-LL	H	5	228.3	-	1964	[62]
Plainview (1917)	chondrite	Chondrites	Ordinary	H-L-LL	H	5	86.9	-	1917	[76]
Potter	chondrite	Chondrites	Ordinary	H-L-LL	L	6	124.6	-	1941	[76]
Pultusk	chondrite	Chondrites	Ordinary	H-L-LL	H	5	12	-	1868	[76]
Roy (1933)	chondrite	Chondrites	Ordinary	H-L-LL	L	5	55.8	-	1933	[86]
Salla	chondrite	Chondrites	Ordinary	H-L-LL	L	6	20.47	-	1963	[87]
Shaw	chondrite	Chondrites	Ordinary	H-L-LL	L	6/7	50.655	-	1937	[88]
Siena	chondrite	Chondrites	Ordinary	H-L-LL	LL	5	110.55	-	1794	[89]
Toluca	octahedrite	Primitive Achondrites		WIN-IAB-IIICD	IAB		142	-	1776	[90]
Turtle River	octahedrite	Achondrites			IIIAB		133.38	-	1953	[62]
Two buttes	chondrite	Chondrites	Ordinary	H-L-LL	H	-		-		-
Vigarano	chondrite	Chondrites	Carbonaceou	CV-CK	CV	3	10.3	-	1910	[38]
Wellman (c)	chondrite	Chondrites	Ordinary	H-L-LL	H	4	76.3	-	1964	[91]

Stony meteorites. Iron meteorites. Story-iron meteorites.

Notes

[1] [Fe/H] ≡ $\log(Fe/H)_{star} - \log(Fe/H)_{Sun}$, where Fe/H is the ratio of the number (or mass) abundance of iron to that of hydrogen.

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