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A Fistful of Mars Exploring the Role of Martian Meteorites in Cultural Heritage and Scientific Inquiry

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Abstract: Meteorites have intrigued humanity for centuries, representing our enduring pursuit of knowledge and exploration of the cosmos' enigmas. These celestial objects have not only influenced artistic expression and the formation of myths but have also fostered scientific inquiry. In this regard, meteorites are crucial to space research, offering valuable information about the early solar system, the formation of planets, and the development of organic compounds. Their analysis aids in deciphering cosmic processes and identifying resources that may support future space missions, making them essential for advancing planetary sciences. Meteorites are also cultural heritage items, with most known samples preserved in natural history museums. This paper deals with the Martian meteorites collected to date, focusing on NWA 16788, the largest individual Martian meteorite recovered so far.

Keywords: Martian meteorites; Mars; cultural heritage

Citation: Franza, A.; Shehaj, X.; Pratesi, G. A Fistful of Mars Exploring the Role of Martian Meteorites in Cultural Heritage and Scientific Inquiry. *Heritage* **2024**, *7*, 6981–6997. https://doi.org/10.3390/heritage7120323

Academic Editor: Nicola Masini

Received: 22 October 2024
Revised: 28 November 2024
Accepted: 9 December 2024
Published: 10 December 2024

1. Introduction and Scope

The allure of meteorites has fascinated humanity since its inception. Thus, it is hardly surprising that there exists a vast amount of literature on these celestial objects, encompassing a wide array of topics that include both scientific inquiries and historical–cultural analyses (e.g., [1,2]). Meteorites represent a source of extraterrestrial material naturally available on Earth, and their investigation provides valuable insights into the early stages of the solar system, the processes involved in planetary formation, and the origin of organic compounds (e.g., [3]).

As reported in the Meteoritical Bulletin Database (MBD), a comprehensive electronic resource provided by the Meteoritical Society (e.g., [4]), 76,728 documented extraterrestrial samples have been recovered to date, along with 6383 provisional names, i.e., meteorites discovered in dense collection areas that have not yet been analyzed and classified (MDB, last update 15 November 2024).

As McCall et al. [5] remarked, it is worth mentioning that most of the known meteorite specimens are housed in natural history museums worldwide. These collections represent a significant scientific heritage and embody tangible and intangible meanings, making them part of a rare and distinctive cultural heritage [6]. Therefore, as McCubbin et al. [7] rightly pointed out, Earth-based collections of astromaterials should be managed according to specialized curation methodologies and techniques known as advanced curation (AC), comprising the development of innovative solutions for sample acquisition, handling, characterization, analysis, and storage. Regarding meteorites, McCubbin et al. [8] underlined how these collections are of pivotal importance for planetary and space science research since they represent a quite inexpensive source of extraterrestrial material useful to enable new scientific discoveries. Meteorite collections are then essential in facilitating sample return missions (SRMs) [9], as they provide the paradigms necessary for analyzing the samples that are brought back (e.g., [10]) and developing AC standards and facilities (e.g., [11]).

From 1969 onwards, manned and robotic SRMs have returned diverse quantities and qualities of pristine materials, mainly from the Moon and near-Earth asteroids (i.e., Itokawa, Ryugu, and Bennu). Future and ongoing SRMs will focus on carefully selecting and retrieving samples from other celestial bodies to be studied in terrestrial laboratories. These missions aim to enhance our understanding of planetary evolution, including Earth itself, investigating potential locations for the sustainable exploitation of space resources and assessing the possibility of long-term human settlement in these environments [12].

Among the celestial bodies within our reach and due to its chemical and physical similarities with our planet [13], Mars has been selected as the target of the first SRM from another internal planetary body since the Apollo lunar landings [14]. The Mars Sample Return (MSR) program is a multi-mission robotic campaign conducted by NASA and ESA to collect, store, and deliver Martian rocks and atmospheric samples to Earth [15]. A comprehensive examination of the primary MRS objectives is beyond the scope of this paper. Nevertheless, an overview of the MRS's aims and the specifications for the design of the sample-receiving facility can be referenced in the works of Beaty et al. [16] and Tait et al. [17].

Until the MSR missions are finalized and the samples collected, Martian meteorites are the only samples of Mars that can be analyzed in terrestrial laboratories equipped with state-of-the-art instrumentation. Martian meteorites are, therefore, crucial for planetary and space sciences because they provide rare, direct samples of Mars's surface and interior, representing a baseline for interpreting data collected by Mars rovers and orbiters and aiding in the planning of future human and robotic missions. Their investigation enables researchers to understand Mars's geological history, giving information about its age, crust, and mantle composition. Furthermore, since most Martian meteorites are magmatic rocks, their study provides insights into Mars's volcanic processes and thermal evolution. Martian meteorites, like Tissint, then reveal clues to Mars's climate because the trapped gasses match the planet's atmosphere, confirming their origin and providing data on its past climate. Some samples also contain water-bearing minerals or evidence of interaction with liquid water, thus helping scientists understand Mars's hydrological history. Moreover, some meteorites, like Allan Hills 84001, have been thought to contain organic compounds, raising questions about the potential for past life and the conditions under which microbial life could have existed on Mars. Finally, comparing Martian meteorites to terrestrial and lunar samples offers invaluable information to understand planetary formation and differentiation processes in the solar system. A comprehensive examination of the different kinds of scientific information Martian meteorites can provide is out of scope here. However, this topic is discussed in foundational and cutting-edge studies such as Mittlefehldt [18], McKay et al. [19], Weiss et al. [20], Nyquist et al. [21], Bridges and Warren [22], Chennaoui Aoudjehane et al. [23], Agee et al. [24], McSween [25], and Udry et al. [26].

Martian meteorites hold significant value not only for science but also as cultural heritage. Their importance extends beyond their scientific data, encompassing historical, cultural, and philosophical dimensions. As outlined by Markley [27], Mars has been the subject of a lively scientific debate, thousands of studies, and the setting for hundreds of novels, stories, movies, and exhibits, acting as a metaphor for discovery, resilience, and the unknown. Martian meteorites are thus a connection to this extraterrestrial environment since there are tangible samples of another planet that foster a sense of wonder and curiosity about humankind's place in the universe. These meteorites challenge humanity to think about life beyond Earth, prompting philosophical reflections on our uniqueness, interconnectedness with the cosmos, and the possibility of exploring and colonizing extraterrestrial outposts [28]. Martian meteorites also represent historical and cultural milestones, since samples like the above-mentioned Allan Hills 84001 have inspired discussions on extraterrestrial life, media coverage, and public fascination [29,30]. These meteorites are thus bearers of global significance since they can be viewed as a shared human heritage whose study and investigation by scholars from different disciplines worldwide symbolize the crucial role played by international cooperation in the advancement of space sciences. Furthermore, Martian meteorites hold educational value since, as rare and unique objects, they are displayed in museums worldwide, fostering discussions about planetary science, space exploration, and Earth's connections to other celestial bodies. Preserving Martian meteorites is, therefore, vital for maintaining their scientific and cultural significance and ensuring that future generations can study and investigate them.

This work aims to contribute to the growing literature on Mars by interpreting Martian meteorites as scientific and cultural heritage. The methodological approach taken in this study is based on analyzing the data from the Meteoritical Bulletin Database to explore the importance of Martian meteorites as a science resource and a part of our cultural legacy. Understanding the link between these two perspectives is essential for refining the best practices employed at every stage of Martian meteorite research. This includes tracking the samples, their placement on the market, classification, cataloging, preservation in natural history museums, scientific institutions, or private collections, and valorization.

2. Background on Martian Meteorites

This work proposes a cultural interpretation of all the Martian meteorites identified to date, spanning from the historical falls documented in the 19th century (i.e., Chassigny in 1815 and Shergotty in 1865) (e.g., [31,32]) to the most recent discoveries, including Northwest Africa (NWA) 16788, which was found in 2023 and is recognized as the largest individual Martian meteorite ever recovered on Earth.

2.1. Number of Discoveries and Geographic Distribution

The Meteoritical Bulletin Database indicates that 392 specimens (including potential paired samples), with a total weight of ca. 367 kg, originated from Mars. One sample (Northwest Africa 14983) has been discredited, while YA1075 has been listed as an undocumented sample. Most specimens (331 units) come from Saharan countries, while 32 are from Antarctica. Only five samples (Chassigny, Shergotty, Nakhla, Zagami, and Tissint) have been recorded as observed falls, i.e., meteorites that were recovered after being seen falling.

Since the initial identification of their Martian origin in the 1970s, the discovery and study of Martian meteorites have steadily increased due to advancements in scientific techniques and systematic search efforts, particularly in meteorite-rich environments (e.g., Antarctica and the deserts of North Africa and Oman). These environments, characterized by minimal weathering and preservation-friendly conditions, facilitate the discovery and retention of meteorites over long periods (Figure 1).

The samples of more remarkable masses are generally sourced from North Africa, which is acknowledged as one of the world's most favorable sites for meteorite recovery. This is due to its unique geomorphological features, such as the continent's extent and extensive desert regions that facilitate the accumulation, visibility, and preservation of the meteorites on the ground [33]. In this regard, Ouknine et al. [34] emphasized that one-sixth of all the meteorites discovered to date and 62% of the known Martian meteorites have been recovered in Africa. The specimens collected from the deserts are conventionally named "Northwest Africa" (NWA) or "Northeast Africa" (NEA), accompanied by a sequential number corresponding to each discovery [35]. However, in the last few years, due to the reporting of the finding coordinates, several collecting areas have been identified and named.

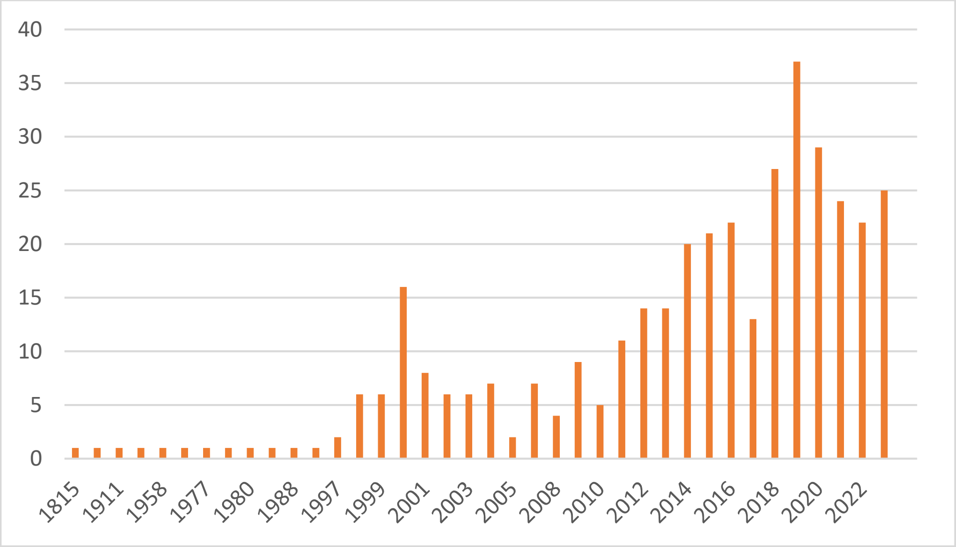

Figure 1. The number of Martian meteorites recovered from 1815 to 2023. Data source: Meteoritical Bulletin Database.

2.2. Classification

According to the literature, Martian meteorites were first identified as a small number of achondrite meteorites named SNCs (Shergottite, Nakhlite, Chassignite), a group of igneous rocks characterized by a mafic or ultramafic composition and a relatively young crystallization age [36,37]. Diverse studies (e.g., [21]) have indicated that these meteorites, due to their late crystallization ages, are more likely to have originated from planetary-sized bodies rather than from asteroids. Mars emerged as the most suitable candidate due to its proximity to the Earth and the evidence of recent active volcanism ([26], and reference therein). The Rare earth elements (REE) pattern also suggested a planetary-sized body origin [36]. The isotopic composition of the trapped gasses ($^{40}Ar/^{36}Ar$ ratio, Ne, Kr, Xe, N_2, and CO_2) in the impact melt glass of shocked shergottites was then similar to the Martian atmosphere that was analyzed during the Viking missions [38]. These gasses were shock incorporated into the melt formed by meteorite impact on the Martian surface [39,40]. Moreover, the analysis of the oxygen isotope compositions in these meteorites [41–43] is consistent with the so-called Martian fractional line, where all points lie along a mass fractionation line that is displaced from terrestrial, lunar, and other basaltic achondrites [36], reflecting a distinct parent body.

In Figure 2, Martian meteorites are grouped according to the nomenclature currently adopted in the Meteoritical Bulletin Database. Among these, 332 samples have been classified as shergottites. It is then interesting to note that three specimens are referred to as “Martian” without any further specification regarding their membership group. The latter are NWA 2646, NWA 10416, and NWA 13179, and they were collected in 2004, 2015, and 2019, respectively.

2.3. Characterization Methods

Characterizing Martian meteorites involves a combination of advanced analytical techniques and methodologies to determine their origin, composition, and history. These methods can be broadly grouped into physical, chemical, isotopic, and petrological analyses. Below is an overview of the primary analytical techniques used to characterize Martian meteorites.

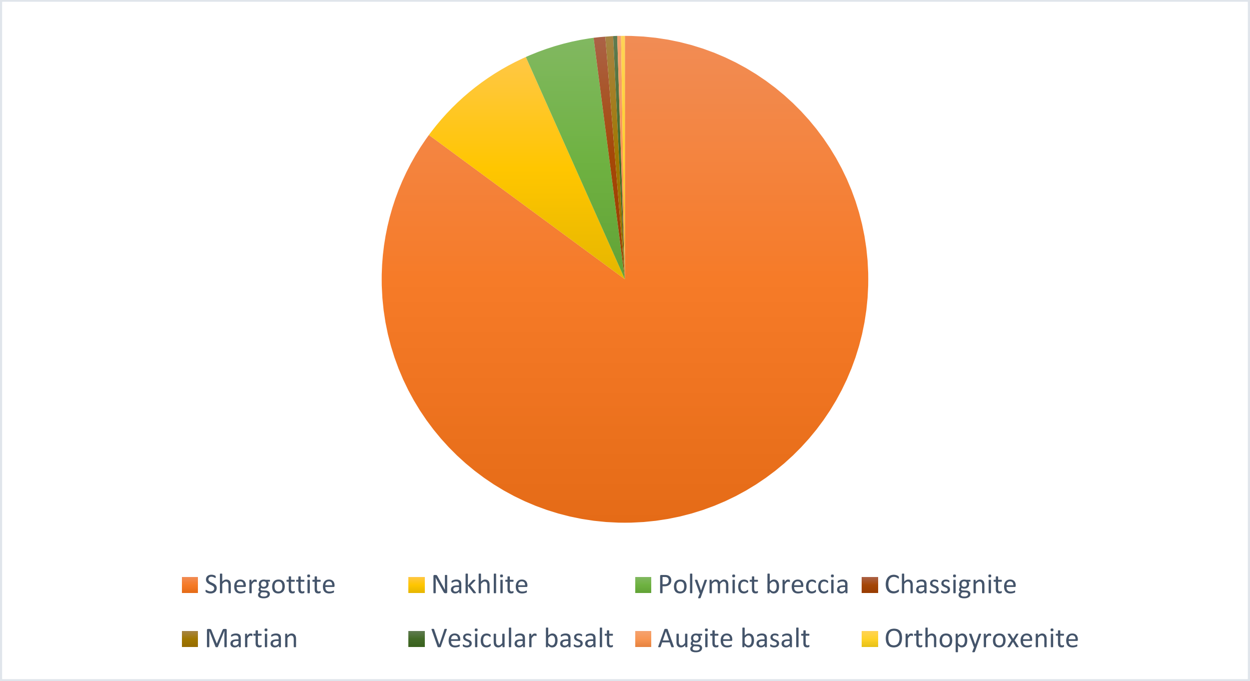

Figure 2. Classification of the Martian meteorites according to the Meteoritical Bulletin Database.

2.3.1. Mineralogical and Petrological Analysis

Petrographic investigations can be carried out using optical microscopes (OM) to examine thin sections under polarized light for studying mineral textures and crystallography. This investigation helps identify igneous textures typical of volcanic or intrusive Martian rocks. Scanning electron microscopy (SEM) provides high-resolution imaging of mineral phases and textures. SEM with energy-dispersive X-ray spectroscopy (EDS) is useful for analyzing elemental composition at the microscale (e.g., [44]). Electron microprobe analysis (EMPA) with wavelength dispersive X-ray spectroscopy (WDS) quantifies the chemical composition of individual mineral grains with high precision and is essential for identifying zoning patterns in minerals and reconstructing thermal histories (e.g., [45]). These techniques confirm the presence of minerals like pyroxene, olivine, and feldspar, common in Martian meteorites (e.g., [46]). Martian meteorites often exhibit shock features from impact events, such as maskelynite (shocked plagioclase) and high-pressure polymorphs of olivine and pyroxene. These phases are identified through methods like X-ray diffraction (XRD) and transmission electron microscopy (TEM) that identifies mineral phases and their crystalline structures. This last technique is used for studying the nanoscale imaging of deformation, alteration phases, and shock-induced features in mineral grains and provides insights into the meteorite's ejection history from Mars (e.g., [47]).

2.3.2. Bulk Chemical Analysis

Inductively coupled plasma-mass spectrometry (ICP-MS) measures trace elements including REE patterns, which explain mantle processes and magmatic differentiation on Mars. X-ray fluorescence (XRF) is useful to determine major elements. These techniques are required to improve the classification of the magmatic rock types and the knowledge of the petrologic processes [48].

2.3.3. Isotopic Analysis

Besides ICP-MS, multicollector-inductively coupled plasma-mass spectrometry (MC-ICPMS), secondary ion mass spectrometry (SIMS), and thermal ionization mass spectrometry (TIMS) are effective techniques to measure many isotopes of cosmochemical interest. Martian meteorites exhibit a unique oxygen isotopic signature (Martian fractional line) that distinguishes them from Earth and other meteoritic materials [36]. Performing noble gas analysis can also be useful to acquire new information on the sample. Martian meteorites often contain trapped gasses, such as argon and xenon, with isotopic compositions that match those of the Martian atmosphere measured by the Viking, Curiosity, and Perseverance missions (e.g., [49,50]). Dating techniques, including Rb-Sr, Sm-Nd, U-Pb, and Ar-Ar, are also used to determine crystallization age and thermal histories. The analysis of radiogenic isotopes helps establish timelines for Martian volcanic and impact events (e.g., [51]). Data from chemical and isotopic analyses are then used to model the magmatic and planetary differentiation processes on Mars. These comparisons are made with geochemical data from Martian surface missions and help scientists correlate Martian meteorites with specific regions or terrains (e.g., [52]).

2.3.4. Volatile and Organic Analysis

Gas chromatography-mass spectrometry (GC-MS) detects volatile compounds and potential organic molecules. As outlined by Douglas et al. [53], Martian meteorites show mainly a basaltic composition. Nonetheless, MRS missions will provide returned samples that will broaden the typologies of material; for example, sedimentary rocks, for ex situ analysis. So, it is mandatory to optimize the analytical protocols using GG-MS to identify organics in materials that originated from Mars before MRS missions are accomplished. Fourier transform infrared spectroscopy (FTIR) is also extremely useful to identify organic molecules and possible biosignatures other than to investigate hydrated minerals and carbonates, which can provide evidence of water–rock interactions on Mars (e.g., [54]). Finally, Raman spectroscopy is used to study carbon phases, including graphite, and to confirm the presence of secondary minerals, such as carbonates or sulfates, formed through aqueous alteration (e.g., [55]).

2.3.5. Magnetic Studies

Paleomagnetic measurements can detect remnant magnetization in Martian meteorites, providing evidence of Mars's ancient magnetic field. For instance, the study by Gattacceca et al. [56] on NWA 7034 revealed that the overall magnetic assemblage of this meteorite sample is partly linked to near-surface hydrothermal alteration, and thus, this sample is an analog source for the magnetization of the Noachian crust (e.g., [57]).

2.3.6. Spectral Matching with Mars

Infrared and visible spectra of Martian meteorites can be compared with orbital and rover spectral data from Mars to identify their potential source regions. These investigations connect meteorites to specific geological contexts on Mars, as evidenced by Hamilton et al. [58]. In this study, the spectra of six Martian meteorites (e.g., Los Angeles, Zagami, ALH A77005, Nakhla, ALH 84001, and Chassigny) have been compared to data from the Mars Global Surveyor thermal emission spectrometer (MGS TES) to map possible source regions for all five known Martian meteorite lithologies (e.g., basalt, lherzolite, clinopyroxenite, orthopyroxenite, and dunite).

The analytical methods and techniques described above are effective not only for confirming the Martian origin of meteorites but also for providing valuable insights into Mars's geological, climatic, and potential biological history. However, a multidisciplinary approach is essential for fully characterizing Martian meteorites. Combining isotopic data with mineralogical, chemical, and textural studies ensures a comprehensive understanding of their origin, ejection, and alteration history. Furthermore, some of these techniques, such as those used to perform isotopic analyses, are quite expensive and require considerable sample preparation, so they cannot be utilized in the primary characterization of new potential Martian meteorites. In this regard, Papike et al. [59] proposed a protocol to determine the chemical composition of silicate minerals in different planetary basalts (e.g., Earth, Mars, and Moon) based on electron microscope analyses. In particular, the authors outlined that the plot of Fe/Mn in pyroxene and/or olivine versus mol% helps define compositional fields significantly different for the meteorites that originated from Mars. Another protocol to characterize Martian meteorites, especially those recovered in Morocco, has been proposed by Larouci et al. [60]. The latter consists of three steps: providing as much field information as possible, studying the sample from a mineralogical and petrographic perspective, and reporting the find classified as a new Martian meteorite to the Nomenclature Committee of the Meteoritical Society to formalize internationally the recovery of the new sample.

2.4. Ownership, Legal Issues, and Ethical Considerations

The ownership of Martian meteorites is a complex issue that intersects with international space law, national regulations, and private property rights. Unlike samples collected during space missions, Martian meteorites are naturally occurring objects that fall to Earth and are governed under terrestrial laws rather than space treaties.

From a broader international perspective, the Outer Space Treaty (OST) [61], negotiated at the United Nations and in force since 1967, was signed by over 110 countries and establishes that celestial bodies, including Mars, cannot be appropriated by any nation or private entity. However, the OST applies to celestial bodies in space. Once Martian materials (e.g., meteorites) naturally fall to Earth, they are governed by national laws rather than space laws. Furthermore, the UNESCO 1970 Convention on Cultural Property [62] provides a framework for protecting meteorites, including the Martian ones, as part of cultural and scientific heritage. However, even in this case, enforcement and adoption vary across nations. A noteworthy exception is the Antarctic Treaty (1959), under which meteorites collected there are treated as international scientific resources and are not privately owned or traded [63].

It has to be noted that Martian meteorites are regulated by the same laws as all meteorites. Schmitt [64] highlighted that in many countries, meteorites found on private land belong to the landowner, while those on public or state-owned land often become state property. For example, U.S. law permits private ownership if found on private land but prohibits collecting on federal land. An in-depth review of the public international, transnational, and national laws regarding the ownership of meteorites is reported in Gounelle and Gounelle [65].

It is worth mentioning that most of the Martian meteorites were discovered in Middle Eastern countries and North African regions. In the latter case, Chennaoui Aoudjehane [66] outlined how Morocco has implemented a regulatory framework that sets it apart from other countries in the region and high-density meteorite collection areas, where the exportation of meteoritic samples is generally prohibited. This distinctive regulation allows meteorite hunters to legally collect and export meteorites under clearly defined and straightforward conditions. They must obtain a permit from the Moroccan Geological Survey before initiating their activities and inform the Geological Survey about their discovery, providing data on the coordinates of the findings, the total mass, the number of specimens collected, a photo of the recovered samples (possibly on site), and a preliminary classification. Subsequently, meteorite hunters must deposit 20 g (if the sample is less than 1 kg) or 40 g (if the finding is more than 1 kg) to the Geological Survey. Finally, the Geological Survey provides meteorite hunters with a receipt useful for exporting meteoritic materials abroad.

As underlined by Chennaoui Aoudjehane [66], the deposit of a portion of the findings to the Moroccan Geological Survey, which acts as a repository, helps preserve the local geoheritage and ensures sustainable management of the activities performed by hunters, dealers, collectors, and scientists. In this regard, the Nomenclature Committee of the Meteoritical Society recognizes that a crucial part of the process for approving new meteorites is depositing the type specimens in official repositories. These institutions include museums, universities, government agencies, research institutes, and other organizations committed to housing permanent meteorite collections. Depositing type specimens in a qualified repository guarantees that these samples will be properly preserved and curated over the long term and made available for scientific investigations. Currently, 129 institutions worldwide have been recognized as official meteorite-type specimen repositories by the Nomenclature Committee of the Meteoritical Society. Martian meteorites are part of humanity's shared heritage, warranting protection and accessibility for public education and scientific study.

Concerning this topic, data from the Meteoritical Bulletin Database show that most Martian meteorite-type specimens are housed in natural history museums. The most extensive collection is kept at the Burke Museum of Natural History and Culture in Seattle, which comprises ca. 112 samples. This museum, in collaboration with the Department of Earth and Space Sciences at Washington University, also preserves several type specimens that were once part of the meteorite collection at Northern Arizona University. The Museum für Naturkunde in Berlin is home to another important collection of Martian type specimens, encompassing ca. 32 samples. Among the university and institutional collections, it is worth mentioning that the Meteorite Museum of the University of New Mexico preserves 53 Martian type specimens. On the contrary, most of the main Martian meteorite masses (315 samples) are held by private dealers or collectors. Only two meteorites are preserved in a government agency. These samples, Ramlat Fasad 533 and Ramlat Fasad 534 were discovered in 2018 and 2019 in the eponym meteorite dense collection area [67], located in the governorship of Ẓufār (Oman), and are kept by the local Ministry of Heritage and Tourism.

The increase in discoveries of Martian meteorites over the years (Figure 1) has influenced the market regarding collection practices. As Entrena Utrilla and Welch [68] stated, initially, Martian meteorites were usually sold at a high price due to their limited availability. This occurrence has prompted the emergence of new agents, such as new collectors, investors, and even speculators, who, akin to their counterparts in the art market [69], prioritize esthetic and financial motivations over scientific factors in their acquisitions. For instance, there is a growing interest in purchasing Martian meteorites characterized by remarkable masses to preserve them in their pristine form. According to the findings presented by Chennaoui Aoudjehane [66], the economic potential of these samples, especially if they are of Martian and lunar origins, serves as a substantial source of income for the local communities. Consequently, the discovery and trade of meteorites from these areas can be interpreted as a form of supply chain. The first part of this process primarily involves the nomadic communities where casual, amateur, and expert meteorite hunters are active. Casual hunters usually gather stones that pique their interest and are not in contact with traders or researchers, while the amateurs collect potential extraterrestrial materials motivated by economic reasons and may have acquaintances with dealers and academics. Then there are the expert meteorite seekers, as remarked by Chennaoui Aoudjehane [66], who are extensively trained in finding and identifying meteorites. They have connections with merchants and scientists and can be professional vendors. The last part of the meteorite discovery process encompasses local traders who are acquainted with researchers to provide an approximate classification of the findings. Finally, the intermediaries, usually native people with advanced English language skills, prize and place the meteorites on the international market by networking with scholars, museum professionals, private collectors, and investors [70]. Another interesting aspect of the meteorite finding and trading process is the emerging trend noted by Golia [71]. This trend indicates that extraordinary meteorite samples, particularly those sourced from Mars and exhibiting distinctive physical and esthetic characteristics, are increasingly being sold at renowned auction houses. As outlined by Gounelle and Gounelle [65], the determination of the selling price is influenced not only by the sample's commercial value determined by the auctioneers but also by its official recognition and classification as an extraterrestrial material grounded on scientific evidence. This finding underscores the pivotal role played by characterization procedures for establishing the provenance and classification as well as the scientific and economic value of a meteorite specimen (e.g., [72]).

The ownership of Martian meteorites is, therefore, a dynamic and multifaceted issue. While private ownership and trade are generally legal in many countries, there is growing recognition of their scientific, cultural, and economic significance. Striking a balance between accessibility for scientific research, public education, and private collecting remains a central challenge for policymakers and the scientific community.

3. Case Studies of Martian Meteorites

Case studies of Martian meteorites are crucial for advancing our understanding of Mars's geological, atmospheric, and potential biological history. By examining individual meteorites in detail, case studies create a bridge between microscopic analyses and macroscopic planetary processes, enriching our collective knowledge of Mars and the broader solar system. Furthermore, case studies provide focused, detailed insights into specific samples, improving the understanding of Martian meteorites as scientific and cultural heritage.

For instance, the Tissint meteorite is one of the most significant Martian meteorites discovered, valued for its scientific importance and role in cultural heritage. Tissint fell on Earth in the early hours of 18 July 2011, near the village of Tissint in the Tata Province of southern Morocco. It was observed as a bright fireball streaking across the sky, followed by a loud explosion. The meteorite fragmented upon entry, scattering pieces over a wide area that were quickly collected by the locals. The pristine nature of these findings, due to their rapid recovery and minimal exposure to Earth's environment, makes Tissint one of the most uncontaminated Martian meteorites available for study. As evidenced by Chennaoui Aouidjehane et al. [23], Tissint provides insights into the Martian mantle and volcanic processes. It also contains signatures of water–rock interaction, suggesting that the sample was exposed to liquid water at some point on Mars (e.g., [73]). Furthermore, as evinced by Schmitt-Kopplin et al. [74], the presence of complex carbonaceous compounds reveals heterogeneity in organic speciation within the minerals grown in the Martian mantle and crust that may have evolved over geological time. Tissint is, therefore, an invaluable scientific heritage, but it is also an important cultural heritage object, acquired by museums worldwide (e.g., the Natural History Museum in London and the University of Alberta Meteorite Collection), whose discovery highlights Morocco's significance as a source of Martian meteorites. Moreover, the rapid collection of Tissint fragments by residents underscores the cultural importance of meteorite hunting in Moroccan society [75].

Another interesting case study is represented by NWA 16788, which is the largest individual Martian meteorite recovered so far. On 16 November 2023, a meteorite hunter, whose identity remained undisclosed, discovered a sizable stone in the Agadez Region of the Sahara Desert, at ca. 90 km to the west of the Chirfa Oasis in northwestern Niger. The sample was notably large, with a weight of 24.67 kg. Once sold by the local community to an international dealer, the sample is now held by a private gallery located in Arezzo (Tuscany, Italy) (Figure 3).

To date, research on NWA 16788 has focused exclusively on characterizing the sample and establishing its provenance from Mars. However, an in-depth study has uncovered compelling data highlighting its significance from the dual perspectives of meteoritics and science outreach. From a scientific viewpoint, NWA 16788 represents a remarkable specimen, distinguished by both its mass and nature. Concerning the first point, it should be noted that this specimen, with a mass of 24.67 kg, constitutes the largest individual meteorite from Mars recovered thus far. Other individual Martian meteorites of significant mass are Zagami (18 kg), Taoudenni 002 (14.51 kg), and Yamato 00593 (13.71 kg). It is then worth mentioning Amgala 001, whose total known mass is 34.67 kg. This mass accounts for all the samples that have been collected, while the weight of the main individual is 5.2 kg.

Figure 3. NWA 16788 is the largest individual Martian meteorite recovered thus far (ca. 24.6 kg). The sample is kept at a private gallery in Arezzo. Two slices are preserved at the University of Firenze.

The discovery of meteorite samples with considerable mass presents a significant challenge, particularly when these specimens originate from a planetary body like Mars. In this case, the relevant mass of the planet generates a gravitational field of 3.73 m/s^2, which results in an escape velocity from the surface of 5.03 km/s. As the mechanism by which Martian material is ejected into space is tied to impact processes, it is important to consider a range of parameters to quantify these processes effectively. In particular, the mass and velocity of the impacting asteroid determine the energy of the impact. With respect to the material that has been ejected, it is apparent that, under conditions of constant energy, an increase in mass corresponds to a decrease in its ejection velocity. In this scenario, the pre-atmospheric mass of NWA 16788 was significantly higher, taking into account that the estimates for mass ablation indicate a weighted mean (or median) ablation rate of approximately 85% [76]. During an impact event, ejecting materials can accelerate significantly, potentially reaching orbital or escape velocity. Canup and Agnor [77] suggest that materials in orbit may coalesce into a moon, while materials ejected in amounts exceeding the impactor's mass can lead to the net erosion of the target, as noted by Asphaug et al. [78]. According to Marinova et al. [79], a particle is considered in orbit when its velocity falls between circular orbital velocity and escape velocity, and its angular momentum exceeds that of a circular orbit at the planet's radius. A particle is defined as escaping when its velocity exceeds the escape velocity. It is important to note that research conducted by Pierazzo and Melosh [80] and Marinova et al. [79] indicated that the maximum mass ejected, while maintaining constant impact energy, occurs during massive impacts characterized by low velocities (6–10 km/s) and high angles (30–60°). Furthermore, Marinova et al. [79] found that across the full spectrum of simulated impact energies, velocities, and impact angles less than 45°, the mass that escapes is between 3 and 100 times greater than the mass that is placed into orbit; in contrast, higher impact angles can lead to an escape of material that is up to 1000 times greater than that which enters orbit. For small, head-on impacts, combining the ejection velocity relationship of Melosh [81] and the impact scaling relation of Wilhelms and Squyres [82] suggests a relationship of $\boldsymbol{V_{ej}} \propto \boldsymbol{V_{imp}^{0.58}}$, where $\boldsymbol{V_{ej}}$ is the maximum ejection velocity. It is significant to note that Melosh [81] demonstrated that, in the case of small impacts, the peak ejection velocity is proportional to the crater's diameter, while the ejection velocity decreases radially from the point of impact. This indicates that the material closest to the impact site is ejected at higher velocities, whereas material farther from the crater is ejected at lower velocities. Consequently, both the ejected and the orbiting masses increase with the size of the crater. Although upwards of 90 million impact craters are greater than 50 m on the Martian surface, only ~19 large primary craters are potentially responsible for the ejection of Martian meteorites ([83], and reference therein). Hence, the probability that tons of material from Mars might have escaped the planet's gravitational field is significantly elevated, although the probability that this material falls on the Earth is very low. However, the highly energetic impacts that result in the ejection of Martian material also have an important effect on the material itself. The evidence is that many Martian meteorites have undergone a significant shock effect, often resulting in the amorphization of plagioclase (maskelinite) and other phases. These shock effects can also cause fracturing that will result in fragmentation. Even if the material maintains integrity during the ejection phase, it may likely fragment as it enters the atmosphere, mainly because of the strong pressure gradient to which it is subjected. For NWA 16788, the occurrence of maskelinite and melt pockets suggest a high-shock stage during its ejection. This aligns with previously reported observations indicating that the ejection of large amounts of materials requires a highly energetic impact. Regarding the characterization of NWA 16788, it is worth mentioning that contrary to what is reported in the Meteoritical Bulletin Database, further investigations revealed that this sample is an olivine microgabbro, a rock type that is considered to be rare within the shergottite group.

From a museological perspective, the peculiar features of NWA 16788 allowed it to be showcased at the Italian Space Agency during the 2024 European Researchers' Night, i.e., an annual event synchronizing initiatives across European countries to enhance public engagement in research since 2005 [84]. An explanatory panel accompanied the exhibition of NWA 16788, providing insights into the meteorite's recovery history, summarizing the principal discoveries from analytic investigations that established its Martian origins, and underscoring its scientific and cultural relevance for future Mars exploration missions (Figure 4).

Furthermore, two members of the research team served as informal science educators (e.g., [85]), addressing inquiries posed by the audience. In this regard, Bobbe et al. [86] outlined how informal science educators, including scientists who engage with the public in non-formal environments, play a pivotal role in explaining space and planetary sciences to non-experts, promoting visitors' engagement from initial attraction to a deeper learning experience. They enhance visitors' involvement, fostering a journey from initial curiosity to an enriched learning experience. For example, Golemshinski [87] remarked how popularizing meteorite hunting and recovery procedures can draw students into physics, enhancing their comprehension of specific astrophysical and physical phenomena such as meteoroid atmosphere entry and mechanical dispersion.

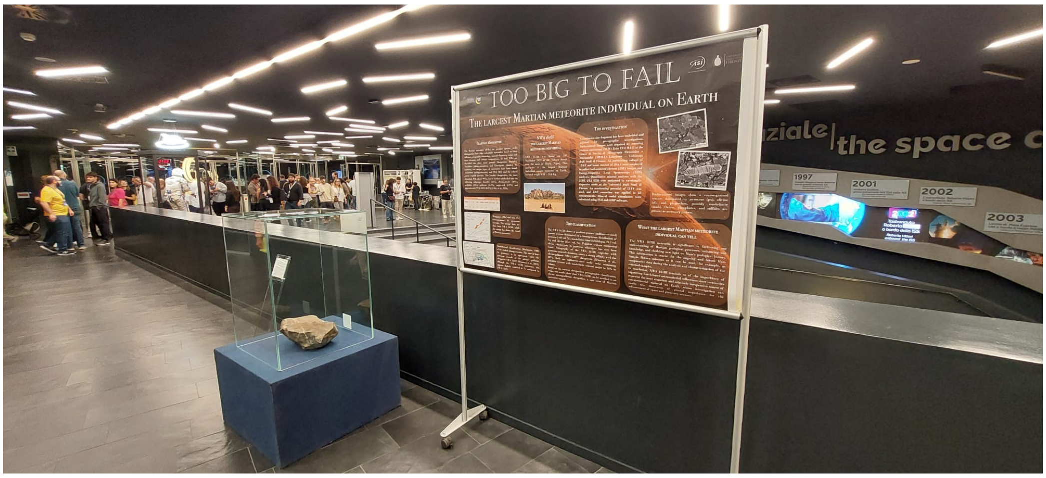

Figure 4. The exhibition of the NWA 16788 meteorite sample at the Italian Space Agency (Rome) during the 2024 European Researchers' Night.

As remarked by Ikuta [88], organizing outreach activities, including the exhibition of extraterrestrial samples (e.g., meteorites and returned samples), contributes to popularizing hard-to-digest concepts while enhancing public awareness of all the scientific, social, and cultural aspects of planetary exploration. The exhibition of Martian meteorites, particularly those with unique attributes like NWA 16788, can enhance the public's understanding of temporal frameworks, research objectives, and governmental financial allocations for significant space initiatives such as the exploration of Mars.

Finally, it is noteworthy to highlight the role of Martian meteorite collections and databases, such as those maintained by the Meteoritical Society, for the systematic cataloging and sharing of meteorite data. The case study presented here concerns the cataloging procedures and data-sharing policies employed by the Italian Museum of Planetary Sciences (hereinafter MISP) in Prato (Tuscany, Italy) and focuses on the Martian meteorite samples preserved by this institution. MISP is the only Italian museum entirely devoted to the display of meteorites and the illustration of planetary sciences [89]. Its meteorite collection encompasses over 1500 samples, including complete individuals, fragments, end cuts, slices, and thin and thick sections (291 and 184 units, respectively) [90]. The MISP meteorite collection comprises 15 Martian samples: Dar al Gani 670 (one complete individual, one etched part slice, one slice, and two thin sections); NWA 15364 (one fragment); NWA 4222 (five slices, one thin section, and one end cut); and NWA 7387 (one thin section). Apart from NWA 15364, the other samples have been cataloged using the Italian national standard BNPL [91], and the catalog records have been published in full open access on the General Catalog of Cultural Heritage database (http://catalogo.beniculturali.it, accessed on 10 December 2024), managed by the Italian Ministry of Culture. The latter database comprises files (3,022,262 records to date) about cataloging the entire Italian cultural heritage. Among the 66,893 natural items, 1094 are meteorite specimens. The choice to include the Martian meteorites kept at MISP within the General Catalog of Cultural Heritage database helps to increase public awareness of the Martian meteorites as scientific and cultural heritage. The database serves as a central repository for the meteorites preserved in Italian natural history museums and research institutions, facilitating the open-format dissemination of information while reducing redundancy and ensuring that scientists worldwide can access a unified body of knowledge.

4. Conclusions

Interest in Martian meteorites has grown significantly over the years due to advancements in planetary science, space exploration, and our desire to understand Mars as a potential habitat for life. The rarity of Martian meteorites makes them highly sought after by collectors and museums, driving demand and increasing public awareness. These samples, therefore, represent scientific and cultural heritage that deserves to be correctly preserved, classified, and valorized for future generations of researchers and amateurs. As noted by Viotti [92] in discussing the different cross-disciplinary perceptions of Mars, Martian meteorites combined scientific and humanistic meanings belonging to a global spacefaring culture (e.g., [93]) and thus can foster public engagement toward the social and cultural aspects of the human exploration of outer space.

One of the more significant findings from this study is that most of the main Martian meteorite masses are held by investors and private collectors. The second major finding was that, despite their importance for advancing space and planetary sciences, many Martian meteorites are investigated solely to confirm their extraterrestrial origin and to obtain an undetailed classification. To partially fill this research gap, this work presented the NWA 16788 sample, the largest individual Martian meteorite collected so far, from a scientific and cultural perspective for the first time to the scholarly community.

While from a planetary and space sciences point of view, the importance of Martian meteorites is well established, their understanding as a cultural heritage may be improved. On this subject, Van Geert [94] noted that the exhibition of meteorites represents a unique opportunity for museums to explore the links between geological collections and contemporary culture. This statement is particularly valid when applied to Martian meteorites since they have captured the interest of scientists, educators, collectors, and the general public over the years. The public fascination is indeed fueled by their uniqueness, the process by which they reach Earth, and their connection to a broader narrative regarding cosmology, space exploration, planetary science, and the possibility of discovering clues to ancient Martian life. In this regard, Blumenfeld et al. [95] stated that to make the most scientific and culturally significant samples available worldwide for research and educational activities through new advanced curation standards and valorization strategies, it is possible to create virtual 3D meteorite reconstructions. The latter preserves the exact structure of the samples, ensuring long-term accessibility even if they were altered, lost, or damaged. As remarked by de Vet [96], these models are useful tools for blended learning in academic teaching and outreach activities, since they can be inspected by rotating and zooming. At the same time, annotations in clickable pop-ups can provide cultural information and scientific data about the displayed specimens. Furthermore, these models make the Martian meteorites accessible to educators, students, and visitors who might never have the opportunity to see the samples personally, democratizing access to these rare resources.

On this basis, museums and exhibitions could focus in the future on implementing and using 3D reconstructions of Martian meteorites to create interactive displays, making the study of these samples and the planet Mars more engaging and comprehensible for visitors [97].

Finally, these models could be included in the databases for Martian meteorites to foster a deeper understanding of Mars. Three-dimensional reconstructions allow researchers to examine the morphology of meteorites in high-resolution detail without physical handling and the need for transporting the samples between different facilities. These models can be integrated with analytical tools to simulate processes like impact deformation or identify similarities and differences in the diverse samples to improve the understanding of Martian geology (e.g., [98]).

Author Contributions: Conceptualization, A.F., X.S. and G.P.; methodology, A.F., X.S. and G.P.; formal analysis, X.S.; writing—original draft preparation, A.F., X.S. and G.P.; writing—review and editing, A.F., X.S. and G.P.; funding acquisition, G.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research was financed by the Space It Up project funded by the Italian Space Agency, ASI, and the Ministry of University and Research, MUR, under contract n. 2024-5-E.0—CUP n. I53D24000060005.

Data Availability Statement: The original contributions presented in the study are included in the article, and further inquiries can be directed to the corresponding author/s.

Acknowledgments: The authors thank Luca Cableri, owner of the NWA 16788 meteorite, for allowing the sample study, and the Italian Space Agency for arranging the meteorite's public display at its headquarters.

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

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