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Climate Risk and Conservation Challenges at Palermo's Specola Museum

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Abstract: The Specola Museum is housed on the premises of the old Palermo Observatory, founded in 1790, and preserves most of the observatory's cultural heritage. Environmental monitoring following the activation of air conditioning systems in 2018 revealed significant deviations from the historic thermo-hygrometric trends, with particularly dangerous fluctuations in relative humidity. A notable example of the impact of these changes is a 19th-century painted wooden Model of Mars, displayed in the Merz Hall since 2021. In less than two years, the Model has shown progressive damage to its paint layers. Conservation actions have been adopted to stop the deterioration process, but the risk of further deterioration phenomena involving other objects is expected to increase substantially in the absence of intervention. This paper presents the outcomes of a preliminary study on the thermo-hygrometric conditions in the Merz Hall. Based on the European Standard EN 15757: 2010 and the Italian Legislative decree of 10 May 2001, safe ranges for temperature and relative humidity have been identified for the long-term preservation of the collection. These findings will inform future climate management strategies in the museum.

Keywords: scientific collection; preventive conservation; environmental monitoring; astronomical observatory; model of Mars; European standard; indoor climate; dome-shaped room

Citation: Carotenuto, M.R.; Chinnici, I.; Camuffo, D.; della Valle, A.; Prestileo, F.; Megna, B.; Cavallaro, G.; Lazzara, G. Climate Risk and Conservation Challenges at Palermo's Specola Museum. *Heritage* **2024**, *7*, 7165–7187. https://doi.org/10.3390/heritage7120331

Academic Editor: Kristian Fabbri

Received: 25 October 2024
Revised: 7 December 2024
Accepted: 10 December 2024
Published: 14 December 2024

1. Introduction

In 2022, an alarming sign of deterioration was observed in a painted wooden Model of Mars housed in the Specola Museum in Palermo. This 19th-century artefact was displayed inside a showcase in the "Merz Hall" for approximately 20 years without any evident deterioration sign. However, in 2021, the object began to show accelerated damage, with noticeable flaking of its pictorial layers (Figure 1). The damage was due to a lower relative humidity (RH), which generated internal stresses and cracking and swelling of the paint. Along the cracks, some fragments of the pictorial layer lost their cohesion and generated flaking.

The damage highlighted the urgent need to improve the environmental conditions in Merz Hall.

The critical role of indoor climate in museums for the conservation of historical collections is well documented [1–6]. It may either trigger or aggravate the decay processes of the materials constituting the objects through chemical, physical, or biological mechanisms, thereby affecting their longevity and value.

(a) (b) (c)

Figure 1. The different conservation conditions of the Model of Mars in (**a**) 2020, (**b**) 2022, (**c**) 2023.

Each object responds peculiarly to environmental conditions, based on its composition, conservation history, and adaptations to environmental variability over time. In cases where multiple materials coexist within a single object, complex interactions may lead to pathologies that differ from those the materials would develop individually. Many of these dynamics remain insufficiently understood and, today, are further complicated by anthropic factors and climate change-related effects [7–13].

Preserving entire collections thus becomes a complex task requiring the identification and management of a climate that balances the diverse needs of different materials. This challenge is magnified in museums housed within historical buildings, which often present structural and environmental limitations. Interventions in such buildings are further constrained by the imperative to respect and preserve the building itself as a cultural artefact [14]. The Specola Museum, situated in the historical Observatory atop the 12th-century Royal Palace, exemplifies such complexities. Here, balancing the preservation of both the building and the collections necessitates carefully tailored conservation strategies that align with the architectural and historical significance of the site.

Traditionally, museum climatology has relied on defining optimal environments as fixed, narrow thresholds for indoor climate variables to apply to the same category of materials, regardless of their actual conditions, features in play, and past climatic conditions in which they have been preserved [15,16].

Maintaining such ranges is not only resource-intensive but also difficult to sustain, often leading to reliance on Heating, Ventilation, and Air Conditioning (HVAC) systems. These are expensive to install and maintain and their operation can introduce risks to artefacts [17–20], including undesired air movements, abrupt heat and moisture fluctuations, increased deposition of pollutants, and biodeterioration [4,21].

The introduction of standard UNI EN 15757: 2010 "Conservation of Cultural Property—Specifications for Temperature and Relative Humidity to Limit Climate-Induced Mechanical Damage in Hygroscopic Organic Materials" [22] has provided a re-evaluation of the acceptable variability range for the temperature and relative humidity values considered "safe", identifying broader and more realistically sustainable ones in an attempt to minimize the total effect of numerous reactions and processes [23,24]. This standard also introduced the concept of a "historic climate", defined as the climate conditions in the microenvironment where a cultural heritage object has always been kept or kept for an extended period (at least one year). Organic materials, in particular, are assumed to have acclimatized and adapted to the most frequent temperature and RH levels and fluctuations experienced over their lifespan, facing even yield formation or crack. Such adaptations enable the object to withstand the seasonal and daily variability in climatic forces and to persist in the environmental conditions with which it has reached equilibrium [15,25–27].

However, any significant deviations from the historic climate—even when aimed at theoretically improved conditions—can pose serious risks to collections, especially when prior environments have been suitable for preservation. The standard acknowledges such risks and emphasizes corrective measures only in cases where the historic climate has been detrimental to conservation [26].

When planning environmental requirements for the long-term preservation of cultural collections, it is therefore crucial to study the objects, their climatic history, and the performance of the building housing them [28–30]. Aligning the indoor climate with the natural situation determined by the building and the local climate minimizes potential variability in the event of system failures and ensures a sustainable approach to conservation [31]. A comprehensive risk assessment is essential for identifying and prioritizing mitigation strategies for the most serious risks [32]. Such an approach is also recommended by the Decree of 10 May 2001 [14] and article 29 of the Cultural Heritage and Landscape Code (Legislative Decree 42/2004) [33].

The case of the Model of Mars clearly illustrates the risks associated with the departure from the historic climate to which the objects had adapted, particularly when attempting to achieve temperature and relative humidity values pre-determined as “ideal” by existing norms. In this paper, the results of the climate risk analysis conducted on the indoor environment of Merz Hall will be presented, and the unique conservation challenges posed by its dome-shaped architecture will be discussed.

2. The Specola Museum

2.1. Location

The Specola Museum is housed on the premises of the old Palermo Observatory, founded in 1790, atop the Pisa Tower in the 12th-century Royal Palace in Palermo, in an area characterized by expansive adjacent spaces devoid of buildings (Figure 2).

(**a**) (**b**)

Figure 2. (**a**) The blue arrow indicates the ancient Observatory built on the roof covering the 12th-century Pisa Tower in the Royal Palace in Palermo; (**b**) detail of the ancient Observatory, now the seat of the Specola Museum.

The Pisa Tower, the tallest and most robust structure of the entire Palace, was built at the behest of King Roger II in the 12th century. At the end of the 18th century, the tower was chosen as the optimal site for constructing the Royal Astronomical Observatory. The establishment of the Observatory was financed by Ferdinand III of Bourbon and entrusted to the Theatine mathematician Giuseppe Piazzi (1746–1826), who would become the future director of the Specola. The construction began in 1790 and was completed the following year. Originally, it included a large central gallery and two lateral rooms (the Ramsden Circle Hall and the Meridian Hall) (Figure 3a). In 1795, two lateral cubic foreparts (today’s Directors’ Portrait Hall and Meteorological Hall) were added, overlooking the large terrace [34] (Figure 3b). Over time, the building underwent numerous modifications and adaptations. In the 1990s, a comprehensive restoration was undertaken to repair the damage caused by the 1968 earthquake, giving the Specola its current configuration (Figures 2 and 3c) [34].

In 2001, the Specola was converted into a museum to display and preserve the valuable historical heritage accumulated for over two hundred years of activity of the Observatory. The collection on display consists of about 150 objects, including paintings on canvas, plaster busts, clocks, meteorological and topographical instruments, apparatuses for physics and geomagnetism, and astronomical instruments. Among these, the Ramsden Circle, with which Piazzi discovered the first asteroid, named Ceres Ferdinandea, in 1801, stands out as a true masterpiece of 18th-century precision mechanics. Part of the original furnishings of the Specola are still present, including the original showcases designed by Leon Dufourny and the Neo-Gothic "boiseries" designed by Giovambattista Filippo Basile in the Meridian Room [35]. Since 2017, the museum has been part of SiMuA, the Museum System of the University of Palermo, where the collection formally belongs. Since 1988, the management, protection, and enhancement of the collection have been entrusted to the Astronomical Observatory through a formal agreement.

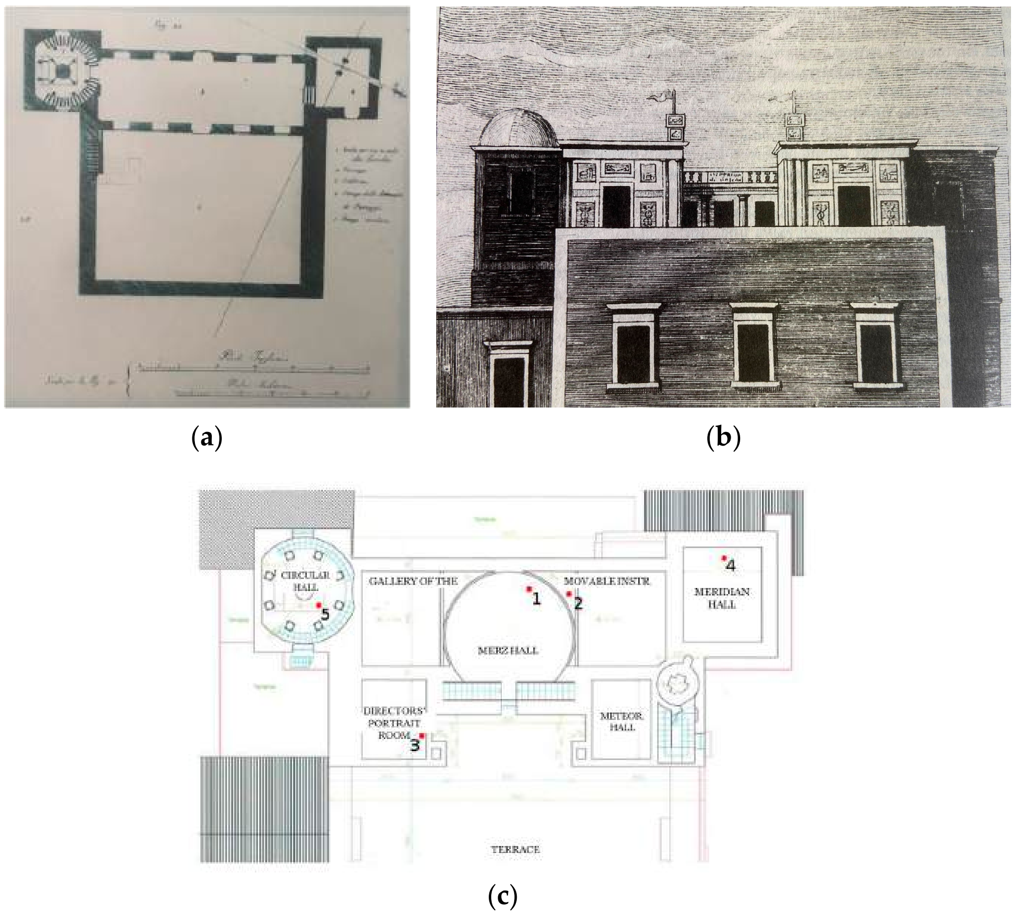


Figure 3. (**a**) Planimetry of the Royal Astronomical Observatory in 1792; (**b**) the observatory in 1802. On the left, the dome of the Ramsden Circle Hall; (**c**) the current planimetry of the Specola Museum after the restorations of the 1990s. Red dots indicate the position of the sensors used for the 2013 and 2019 indoor climate monitoring campaigns.

Inaugurated in 2001, the museum closed in 2010 for renovation works to comply with new fire safety regulations. Today, it only accommodates visitors by appointment, with a maximum of 20 people at a time.

2.2. The Merz Hall

The Merz Hall, also known as the Refractor Hall, was built in 1865 at the highest point of the building, elevated above the Gallery (currently named the "Gallery of Movable Instruments") (Figures 2b and 3c). Access is provided by two staircases: one from the Directors' Hall and one from the Meteorological Hall. It is surmounted by the largest dome of the Observatory and houses the Merz equatorial refractor telescope, from which the hall derives its name.

The room underwent renovation during the restoration of the ancient Specola premises in the 1990s. The dome was reconstructed with a steel structure, covered with wood inside and copper outside, and insulated (Figure 4).

(a) (b)

Figure 4. The Merz Hall before (**a**) and after (**b**) the restorations of the 1990s.

An air conditioning system was installed in 1999. It comprises two ducted units (Daikin, 12.3 kW cooling capacity, 4.5 kW heating capacity) with forced air circulation. The internal components, including the fan coil units and air ducts, are in the gap between the floors and suspended ceilings. These components are accessible through two inspection panels positioned on the room's walls. The working fluid for heating and cooling is a gas contained within a closed-loop circuit that connects the fan coil units to the external condensers, which are mounted on the roof of the Observatory. Temperature regulation is managed by sensors integrated into thermostats placed along the dome's perimeter. Even when the system stops supplying heated or cooled air for temperature control, continuous ventilation ensure steady airflow.

The Hall serves as an exhibition space: in addition to the Merz telescope, clocks, a bust of the Jesuit Fr. Angelo Secchi (1818–1878), and two modern display cases are placed here. These display cases contain spectroscopes and geomagnetism instruments acquired between the late 19th and early 20th centuries. Among the objects exhibited is the Model of Mars.

2.3. The Model of Mars

The Model consists of a wooden support on which the surface of Mars is painted. It is fixed to a wooden pedestal, painted black, and rests directly on a glass shelf inside a modern non-sealed display case made of glass and aluminium (Figure 5a). Lighting is provided by neon lamps, positioned at the top of the case and shielded by a semi-opaque white panel. The back wall and the bottom shelf are covered with blue fabric. The exact period and circumstances of its arrival at the Observatory, as well as its construction date, remain unknown. However, it is plausible to assume it was produced in the second half of the 19th century [35].

Before this period, in fact, studies of Mars were relatively scarce, with only one existing chart of Mars created by the German astronomers Wilhelm Beer (1797–1850) and Johann Heinrich von Mädler (1794–1874) during the perihelia approach of 1830 [36].

In 1856, Mars was near its closest point to the sun (i.e., perihelion) and in opposition (i.e., Mars, the Earth, and the Sun were aligned, with the Earth between them, which is the best condition to observe Mars because it is fully illuminated), allowing for a better view of the planet. Thanks to improvements in glass technology, it was possible to catch more details. Several observers turned their attention to Mars in that period, including the astronomer and astrophysicist Father Angelo Secchi (1818–1878) and his Jesuit colleague Father Enrico Cappelletti (1831–1899). During the opposition of 1858, they conducted an in-depth study of the planet, and from 7 May to 14 August produced an impressive series of drawings of Mars, which are considered fine early examples of the great European tradition of planetary drawing [36].

(**a**) (**b**)

Figure 5. (**a**) The Model of Mars inside the display case in the Merz Hall; (**b**) a detail of the lower part of the Model.

Their work introduced the first colour illustrations of Mars, featuring alleged "channels" on the planet's surface, and paved the way for valuable contributions in the 1860s, as well as for the production of new maps and the first attempt at Martian nomenclature by Richard A. Proctor (1837–1888) in 1867 [36].

The most noteworthy successor to Secchi's Mars work was Giovanni Virginio Schiaparelli, an Italian astronomer from the Brera Observatory in Milan and a close friend of Secchi. Schiaparelli introduced terms like "sea", "bay", "lake", and "cape" for the albedo features on Mars in his 1877–1878 map, using names based on classical and mythological geography of the ancient Mediterranean world [37]. This map set the standard for Mars mapping for the next three decades.

Until 1907, when planetary photography began to replace cartography as the standard of proof [37], maps were the principal and authoritative means of disseminating scientific information about Mars's geography. Three-dimensional representations were not commonly used to present Mars's surface. The few known three-dimensional Models typically depict the planet according to well-established cartographic conventions, such as adding names of albedo features and geometrical lines in the landscape.

The Model preserved at the Specola Museum is a 3D representation of Mars that differs significantly from others known to us so far: it uniquely features a colour representation of Mars's surface, showing islands and peninsulas in light and dark orange, separated by narrow blue waterways (Figure 5).

Like all Mars maps and 3D models of the time, the Model represents the South Pole Cap at the top and the North Pole at the bottom, reflecting how the planet appears when observed through astronomical telescopes from the northern hemisphere. It should be noted that the South Pole Cap and the Southern Hemisphere are accurately depicted in the upper part of the Model, while the North Pole and the surrounding area are incomplete. The brushstrokes become quicker and more abrupt as they approach the North Pole area, leaving the white preparatory layer exposed. Notably, the reference grid used by the author for the Model's construction is visible on that layer (Figure 5b).

It remains unclear whether the author of this Model relied on Schiaparelli's maps—or those of his contemporaries—or rather reproduced what he observed firsthand.

This latter hypothesis seems plausible since the planet's surface is depicted solely with colours, lacking the features that became typical of maps in the second half of the 19th century. Furthermore, the fact that the North Pole area is nearly unpainted would suggest that the Model's author may not have been able to observe this region clearly enough to replicate it. Thus, it is possible that this Model was created for research purposes, based on the author's observational data. The choice to use only colours to represent the observed areas and to transpose these observations onto a three-dimensional form supports the idea that the Model may have been intended as a personal scientific tool rather than a mere copy of existing maps.

3. Materials and Methods

3.1. Indoor Climate Field Survey at the Museum

3.1.1. Indoor Climate Monitoring over the Years

In 2013, after the appearance of salt efflorescence on the walls of the Circular Hall and signs of oxidation on the metal surfaces of the Ramsden Circle, the University of Palermo was commissioned to conduct a monitoring campaign of the thermo-hygrometric parameters in the museum's exhibition rooms. HOBO® UX 100-01116 dataloggers from Onset® (Onset Computer Corporation, Bourne, MA) were installed recording the parameters every hour for one year (from September 2013 to October 2014). In Figure 3c, red dots indicate the position where the sensors were installed within the museum's rooms. The technical specifications of the sensors used are reported in Table 1. The data analysis was performed by calculating a daily average of the sensor recordings. These values were then compared to the suggested values in the dated UNI 10829:1999 standard "Historical and Artistic Interest Assets. Environmental Conditions for Conservation. Measurement and Analysis" [38]. Specific measures and narrow thermo-hygrometric ranges were proposed for each room. In 2018, based on those indications, the air conditioning system was set to run continuously to maintain a temperature of 19 °C in winter, 24 °C in summer, and 22 °C during autumn and spring. A fixed humidity level of 55% was also set for all seasons. Until then, the system had been used only sporadically, mainly for special events.

Table 1. Technical specifications of the HOBO® UX100-011 sensors.

Variable	Range	Accuracy	Interval
Temperature (°C)	−20 °C to 70 °C	±0.21 °C	from 0 °C to 50 °C
Relative Humidity (%)	1% to 95%	±2.5%	from 10% to 90%

Since 2019, all the exhibition rooms have been continuously monitored to assess the impact and effectiveness of the air conditioning system [39]. In 2021, the Observatory agreed with the Institute of Atmospheric Sciences and Climate of the National Research Council (CNR-ISAC) to conduct a more detailed study of the museum's climate.

3.1.2. The Monitoring Campaign in Merz Hall

The Merz Hall has been included in the monitoring campaign since 2013. In the 2019 monitoring phase, the sensors were kept in the same positions as in the previous monitoring campaign (Figure 3c). In May 2021, the sensor placement was modified and the number of devices in the room was increased to study vertical thermal gradients more thoroughly [40,41]. Consequently, an additional datalogger was installed. One sensor was suspended at a height that avoided direct exposure to the air conditioning flow (approximately 2 m above the floor), just below the perimeter of the room's dome (Figure 6a). The second sensor, equipped with Bluetooth, was placed near the telescope objective to record thermo-hygrometric values, approximately 4 m above the room's floor, below the dome (Figure 6b). Both sensors are positioned at a distance from the objects displayed in the room, which are located along the walls.

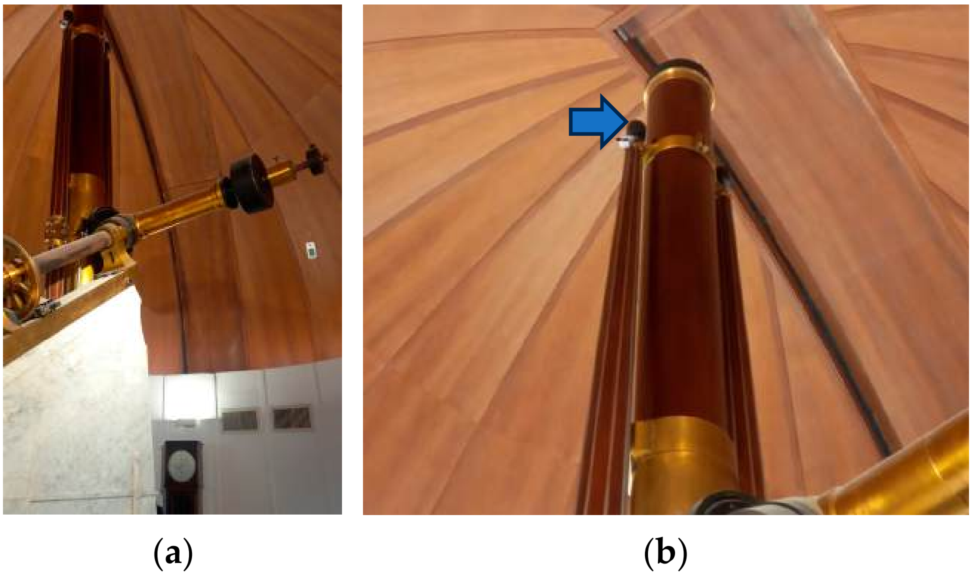


Figure 6. The modified placement of sensors in the Merz Hall: (**a**) one datalogger is suspended from the counterweight of the instrument, and (**b**) the other one is placed near the telescope objective.

The sensors were configured to take readings every 15 min.

Outdoor temperature and relative humidity were considered to evaluate their impact on the internal conditions and the building's performance. The data were recorded by the weather station located on the building's terrace equipped with a TTU 600 Hygroclip HC2 S3 thermo-hygrometer. This device measures temperature from −50 °C to 100 °C and humidity from 0% to 100% RH, with an accuracy of ±0.8% RH and ±0.1 K at 23 °C. The station collects hourly readings of both maximum and minimum values for temperature and humidity. All the data recorded over the years were processed and plotted with Python 3.12 (pandas 2.2.3 and matplotlib 3.9.2 libraries).

Thermal imaging was also conducted to measure the temperature distribution of the dome's surface. A FLIR E6xt infrared camera (Teledyne FLIR LLC, Oregon, USA) was used to observe the radiant temperature of the dome's surface. The images were processed using the FLIR Tools® Mobile app, version 2.6.0.215.

3.2. Diagnostic Study of the Model of Mars

Optical microscopy, Raman spectroscopy, and Fourier transform infrared spectroscopy (FTIR) were performed to investigate the stratigraphy and composition of the paint layers. Small fragments of paint layers, detached over time from the support and collected at the base of the Model, were used for analysis. The analytical results not only provide valuable historical insights into the Model's creation but also inform the planning of conservation methods tailored to the specific needs of the object.

In situ radiographic investigations were conducted to investigate the conservative condition of the wooden pedestal and the support and the construction technique.

To identify the species of wood used in the Model's support, a non-invasive approach was adopted, relying on a macroscopic examination of the visible portion of the wood, corresponding to the upper part of the object's cap. While this approach aimed to avoid any damage to the Model, the visible anatomical features of the wood were not distinct enough to identify the species.

3.2.1. Sample Analysis

Polished cross-sections were obtained by embedding a micro-sample of ground and pictorial layer in a transparent epoxy resin, STRUERS Epofix Kit, removing part of the resin and polishing the section using silicon carbide sandpaper at increasing fines from 500 to 4000 mesh. Observations were made using a LEICA MS5 microscope with a 10× microscope lens, a 4× magnification lens, and a final 2× focusing lens to reach 80× magnification. Illumination was provided by an annular white LED light.

Raman spectroscopy was used to identify the materials in the preparation layers and the pigments used for the two predominant colours of the Model. The Raman spectra were collected using a Renishaw InVia Raman microscope with a 632 nm HeNe laser focused on the sample through a 50× long working distance lens, resulting in a 2-micron diameter analysis spot. Spectra were recorded in the range of 100–1200 cm^{-1} with Wire 3.4 software and analyzed by Spectragryph optical spectroscopy software, version 1.2.16. The reference spectra used for the identification of the materials are reported in [42].

FTIR measurements were performed using a Shimadtsu FTIR 8000. The spectra were acquired between 400 and 4000 cm^{-1} with a spectral resolution of 4 cm^{-1}. A few milligrams of the sample were mixed with 200 mg of reagent grade KBr and analyzed using Raman spectroscopy software. The reference spectra used for the identification of the materials are reported in [43].

3.2.2. Non-Invasive In Situ Analysis

X-ray radiography was performed by a private company, S.T.Art-Test di S. Schiavone & C. S.A.S (Caltanissetta, Italy), using a portable radiographic system consisting of a Poskom X+ PXP-100 CA portable X-ray tube (40 to 110 kVv range) and an AGFA DR 14e radiographic plate with an amorphous silicon TFT detector (150 µm pixel pitch, 2336 × 2836 active matrix, 430 mm × 350 mm active area). Using this setup, 16-bit images with a minimum spatial resolution of 3.36 lp/mm were acquired and displayed instantly on a dedicated laptop with MUSICA software. The images were acquired by rotating the object at various angles to reveal details that could be missed in a single exposure due to the two-dimensional projection. The X-ray tube parameters were optimized, with the pedestal examined at 50 kV and 50 mAs, and the Model at 90 kV and 50 mAs. The higher voltage for the Model was necessary due to the wooden support's thickness and the paint layers' high radiopacity. The data were processed using dedicated software with the application of reconstruction algorithms (image hardening and softening) to highlight structural details and enhance the varying densities (in terms of photon absorption) of the materials in the object [44,45].

3.3. Conservation Treatment

In 2022, conservation actions were adopted to stop the serious deterioration processes. The Model of Mars was first removed from its display case, placed on a stand, and enclosed within a temporary hand-made display case in plexiglass to isolate it as much as possible from the environmental fluctuations in the room. The T and RH values inside the case were monitored using a HOBO® UX 100-01116 datalogger, taking readings every 15 min. This precaution was essential since moving the Model from the Merz Hall would have risked further damage to the object, potentially causing the paint layer to detach. The previously described diagnostic investigations were conducted to investigate the technique of the Model's execution to provide useful supporting data for planning the conservation treatment.

4. Results

4.1. Climate in the Merz Hall

The data related to the period before the full activation of the air conditioning systems provided essential insights into the previous "historic climate" to which the collection had been subjected since the Museum's founding in 2001 until 2018.

A comparative analysis of indoor microclimatic values before and after the activation of the air conditioning systems evidenced significant alterations. Figure 7 shows an increase in the average relative humidity values (%) and maximum daily fluctuations from June to October 2019, compared to the same period in 2014. While the temperature remained generally more stable, sharper and more significant daily excursions occurred compared to the previous situation.

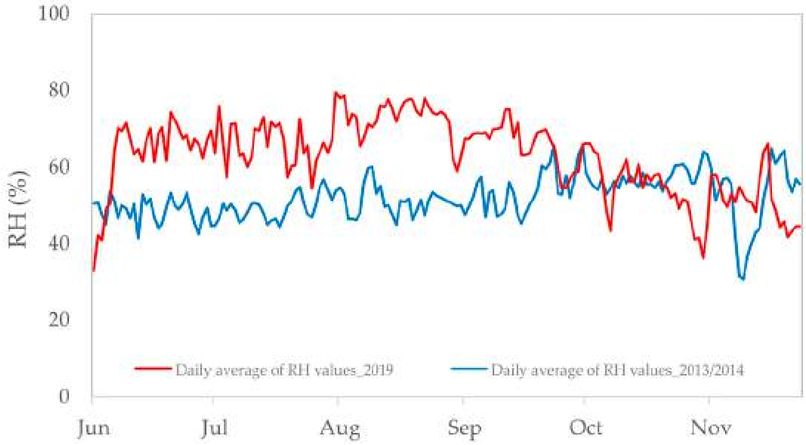


Figure 7. Comparison of the daily average RH values recorded between June and November for the 2013–2014 and 2019 series. It should be noted that between June and October 2019, the average relative humidity values (%) and the maximum daily fluctuations recorded inside the room were higher than those observed during the same period when the air conditioning system was inactive.

To investigate these changes further, Figure 8 compares the daily mean temperature and relative humidity distributions in the Merz Hall for 2013–2014 and 2021–2022. This comparison highlights significant climatic variations between the two monitoring phases. The analysis focuses on daily mean values for corresponding months, providing a consistent basis for comparison.

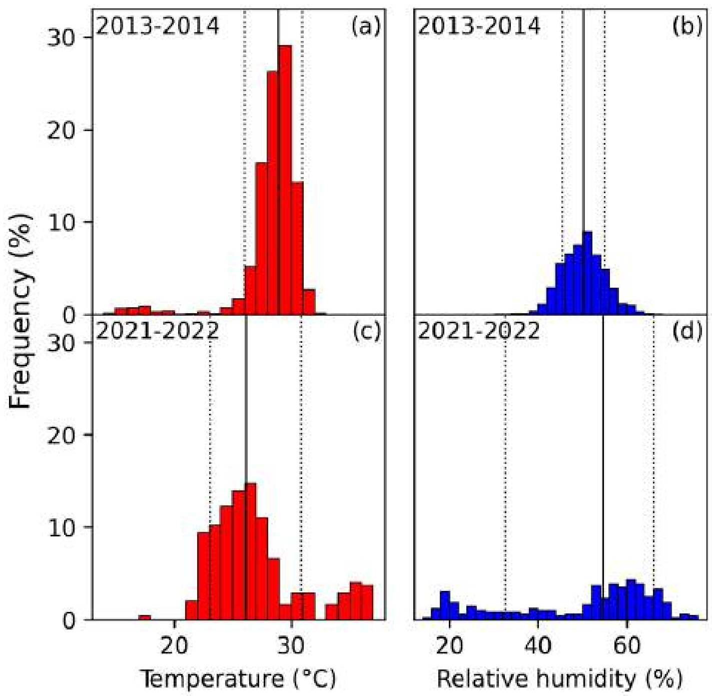


Figure 8. Comparison of daily mean temperature and relative humidity distributions in the Merz room during the periods 2013–2014 (**a**,**b**) and 2021–2022 (**c**,**d**). The continuous vertical lines are the median of the data for each distribution; the dotted vertical lines show the mean ± σ values.

The data show notable shifts in temperature and humidity distributions over time. For the 2021–2022 period, the microclimatic conditions associated with damage observed on the Model are particularly evident. Furthermore, the shift in median values over the years reveals a significant change in microclimatic patterns, with clear implications for material preservation.

Data from both monitoring campaigns were compared with the outdoor thermo-hygrometric values recorded by the weather station located on the terrace of the building to evaluate the impact of the external climate on the internal conditions and the performance of the building that hosts the Museum. In 2014 and 2019, a similar trend in daily fluctuations in average values (%) of RH was observed indoors and outdoors, with lower values inside compared to those recorded outside the museum. In general, the high RH values and significant fluctuations that often occur outside are partially mitigated by the building, which shows good thermal inertia.

However, in 2019, the data show that from June to October, the parameter trends in the room no longer followed the outdoor ones. This year was, in fact, characterized by average daily RH excursions of 10–15%, sometimes larger—between 20–25% and 30%—occurring multiple times within a single day and by prolonged periods of low RH (Figure 9).

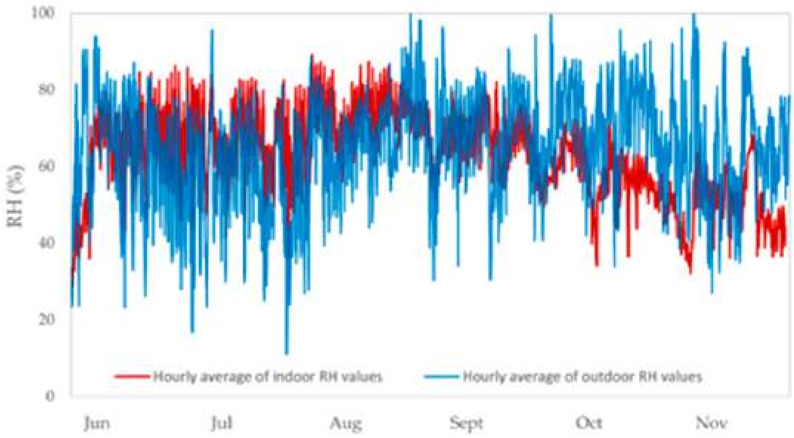


Figure 9. Comparison of the hourly average RH values recorded outdoors and indoors in 2019.

It should be noted that the Hall lacks a system to manage or control RH. As a result, when the room below is heated, especially during the colder months, significant drops in RH occur. A similar situation arises in the event of system failures where excessive heat is introduced into the environment.

Over the years, several episodes were recorded when the RH fell below 40% and occasionally below 30%, albeit for short durations.

An even more dangerous trend in RH was recorded in Merz Hall from November 2021 onwards. The data presented in Figure 10 reveal that between November 2021 and February 2022, the temperatures in the Hall were unusually high, ranging from 35 °C to nearly 40 °C. This indicates that the air conditioning system overheated the environment, most likely due to a failure. This resulted in a drop in relative humidity, frequently to dangerously low levels, well below 40% for several days. During this extended period of low RH, the Model suffered critical failure.

A clear pattern emerges when comparing the conditions inside the dome with those of the external environment during the same period (Figure 11). Initially, up until September–October, the indoor temperature and humidity levels closely matched those of the outside. However, after September, a noticeable shift occurred. Indoor temperatures began to fall below the corresponding outdoor levels, while humidity levels rose above them. This divergence strongly suggests that the indoor environment was becoming increasingly disconnected from the natural external conditions.

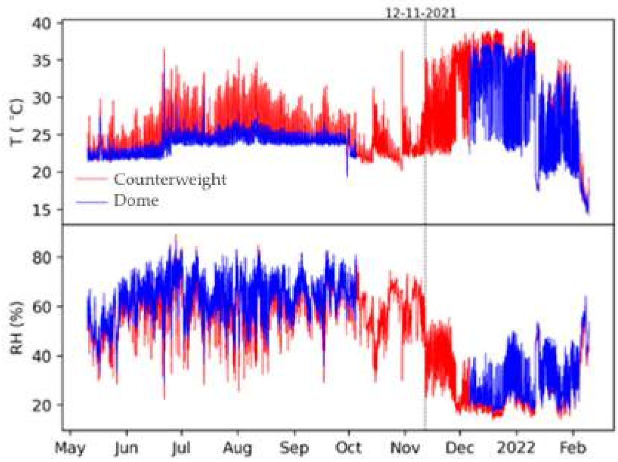
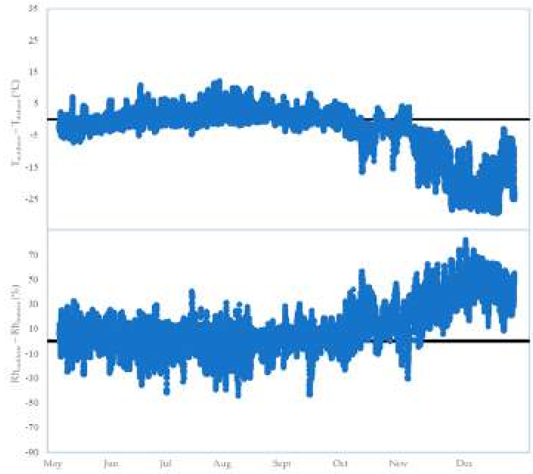
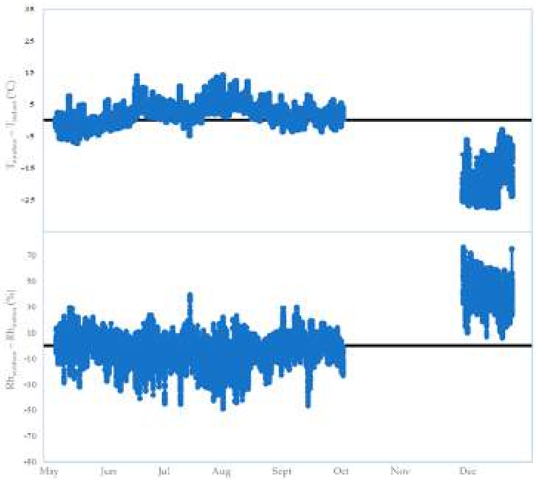


Figure 10. High temperature values were recorded between November 2021 and February 2022. The excessive warm air introduced by the system caused a drop in the RH values, often below 40%.



(**a**)



(**b**)

Figure 11. (**a**) Difference between the temperature and the relative humidity inside the dome and the external values. (**b**) Difference between the temperature and the relative humidity values recorded in the lower part (counterweight) and the external values. Up until October 2021, indoor values followed the outdoor trends. Starting in November, the pattern shifted with indoor T values consistently higher and RH values lower than the outdoor ones. The gaps in the graphs are due to sensor battery failures.

This anomalous trend is more apparent in the graphs related to data recorded in the dome area than in that reflecting the conditions in the lower part of the room. Here, the effects of excessive heating are less visible, likely because warm air tends to rise, concentrating the impact in the upper part of the room, particularly in the dome. This discrepancy between the upper and lower parts of the room further underscores the uneven distribution of temperature and humidity, which could have significant implications for the preservation of materials within the space.

4.2. The Diagnostic Study of the Model

The cross-section of a sample with traces of blue pigment, observed under optical microscopy, revealed two ground layers: a compact white layer beneath the paint layer, and another one, less brilliant and less compact, directly applied to the wood (Figure 12). The layers appeared well-adhered and cohesive. Figure 12 shows the thickness of each layer.

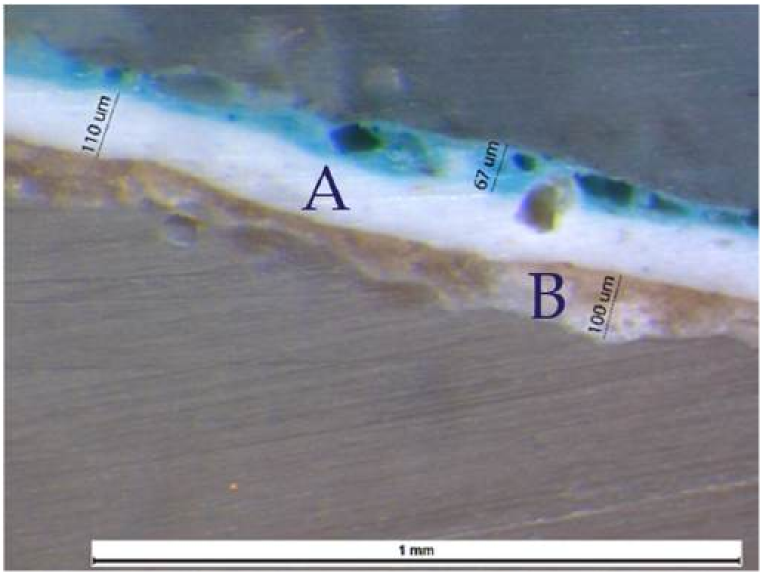
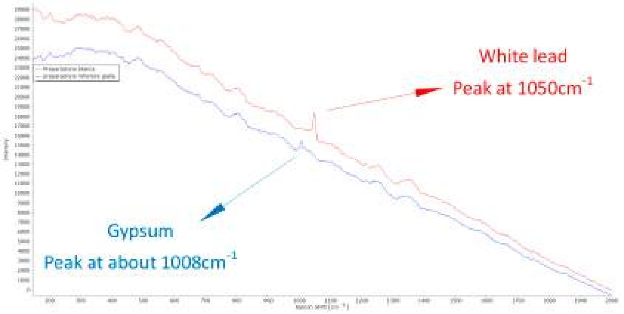


Figure 12. Cross-section of a fragment of the pictorial layer with blue pigment, under visible light, with metric scale. Two ground layers (A and B) beneath the blue paint layer are visible.

Raman spectra of layer A showed a peak at approximately 1050 cm^{-1}, indicating the presence of white lead while layer B exhibited the characteristic peak of gypsum (Figure 13a). In Figure 13b, the spectra of the orange and blue pigments are reported. The spectrum of the blue pigment showed a main peak at 2140 cm^{-1}, consistent with Prussian blue. The orange paint layer exhibited the typical peak of red lead (Pb_3O_4) at around 120 cm^{-1}, along with the peak of white lead at 1050 cm^{-1}.

Infrared spectra of the ground layer (Figure 14) confirmed the presence of gypsum, indicated by peaks at 1119 and 601 cm^{-1}, and double peak at approximately 3406 cm^{-1}. The peak at around 1400 cm^{-1} is associated with both calcium carbonate (peak at 877 cm^{-1}) and white lead (peak at 675 cm^{-1}). The spectra also showed a double amino peak between 1630 and 1550 cm^{-1}, suggesting the presence of a proteinaceous adhesive in the ground layer.

The images obtained by X-ray radiography revealed a “tenon and mortise” joint system between the Model and its wooden pedestal (Figure 15a). The tenon, carved from the wooden rod, is inserted into a mortise cut into the sphere, with the mortise being slightly larger than the tenon. Additionally, a modern screw was visible, securing the base to the rod by penetrating about one-third of its length (Figure 15b). Note that both the base and the rod exhibit numerous insect exit holes, visible due to the complete radiolucency of the black varnish applied during a previous restoration. Most of the holes had been filled.



(a)

(b)

Figure 13. (**a**) Raman spectra of the ground layers shown in Figure 10. White lead is identified in layer A, while layer B contains gypsum; (**b**) Raman spectra of the pictorial layers reveal the presence of Prussian blue in the blue layer and red lead in the red paint.

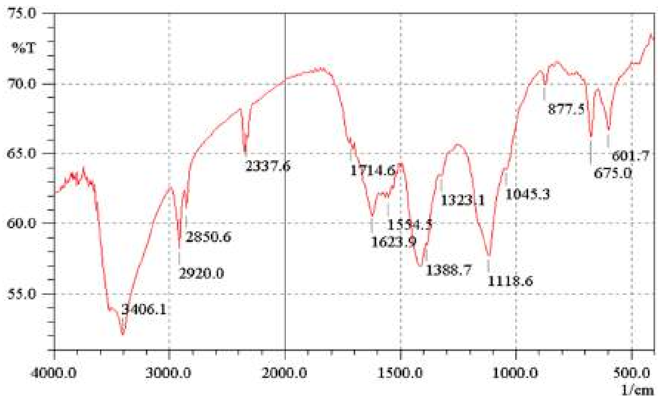


Figure 14. FTIR spectra of the sample shown in Figure 12.

(**a**)

(**b**)

Figure 15. (**a**) The wooden sphere; (**b**) the painted wooden structure anchoring the Model.

Regarding the Model, the two ground layers were easily distinguishable due to their differing radiopacities, particularly in areas where one of the layers was partially detached. The ground layer applied directly to the wooden support appeared more radiolucent than the superficial layer containing white lead (Figure 15a).

The X-ray images also documented the exit holes from wood-boring insects and the fractures in the wooden support, running parallel to the wood grain. This pattern of cracks and detachment aligned with the wood grain strongly suggests that thermo-hygrometric stresses, which induced volumetric changes in the wood, are likely the primary cause of the degradation observed on the surface of the wooden sphere.

The radiographs provided another crucial detail: the wooden support is not hollow but was carved from a single piece of wood. At high magnification, lathe work marks on the wooden sphere, with circular and transverse patterns relative to the central axis, are recognizable. The fact that the Model is made of solid wood explains why it did not suffer significant fractures during humidity fluctuations, as a solid sphere requires more time to reach an equilibrium with the moisture content of the surrounding environment. Presumably, the RH variations were shorter than the response time of the object [46].

Additionally, the presence of paint layers, likely oil-based, may have formed a protective vapour barrier that mitigated the effects of environmental climatic variations, particularly high-frequency fluctuations such as daily RH changes that primarily affect the superficial zones of the wood [47].

5. Discussions

Ensuring the specific thresholds for temperature and relative humidity suggested by the UNI 10829:1999 standard required the activation of an air-conditioning system.

By analyzing data collected between 2013 and 2014, it was possible to assess the climate to which the displayed objects had been acclimated from the museum's founding up until 2019. The data revealed that the room's climate followed a stable, seasonal pattern before the system's activation, smoothed by the building's thermal inertia. However, post-activation, the frequency and intensity of T and UR fluctuations significantly increased, exceeding the natural variability previously observed.

The comparative graphs (Figures 7 and 8) clearly illustrate the difference in RH trends before and after the system's activation. A comparison with external conditions highlights that the internal climate was far more stable when the conditioning systems were inactive. The current management of the system brings a climate that contrasts sharply with previous conditions, indicating that the climate the objects had adapted to was disrupted, albeit with the intention of preservation.

The climate control systems have therefore introduced complications, particularly when failures occurred, as happened in November 2021 (Figure 10).

The specific architectural features of Merz Hall introduce additional factors that make indoor climate management more challenging and must be taken into consideration when planning its regulation. Primary concerns include the upward movement of warm air from lower exhibition areas, air stratification, and the influence of infrared radiation (IR) emitted from the dome.

The Merz Hall is located above the other exhibition spaces of the Specola Museum, which are frequently used for various purposes. In particular, the Gallery of Movable Instruments often hosts conferences, seminars, and meetings and occasionally functions as an office space. The use of the Gallery as an office increased during the COVID-19 pandemic due to the need for an additional workspace for employees. On such occasions, the air conditioning systems were generally adjusted to provide comfortable thermal conditions for the occupants.

Although the Merz Hall itself is not used for multiple purposes, efforts to ensure comfort in the lower rooms inevitably impact its climate. Warm air generated in these lower spaces during colder months ascends into the dome, creating a thermal gradient. This stratification can lead to uneven temperature and humidity conditions and the continuous influx of warm air can lead to risky fluctuations in the RH levels.

The other critical factor is the infrared radiation (IR) coming from the dome. In dome-shaped rooms, IR is generated by the dome itself, being exposed to sunlight during the day. The dome, built with high thermal conductivity materials, absorbs solar radiation and re-emits it as IR into the indoor environment during the daytime. This re-emitted IR can significantly exacerbate air stratification issues and further destabilize the indoor climate. Moreover, prolonged exposure of the objects on display to IR can accelerate their ageing process, leading to the fading of colours, the degradation of organic materials, and the embrittlement of polymers.

Thermal imaging captured with an infrared camera reveals that the dome reaches high temperatures, particularly in the metallic sections of the structure. The thermogram in Figure 16, taken in June 2023 in the afternoon, shows the radiant surface temperatures of the dome materials.

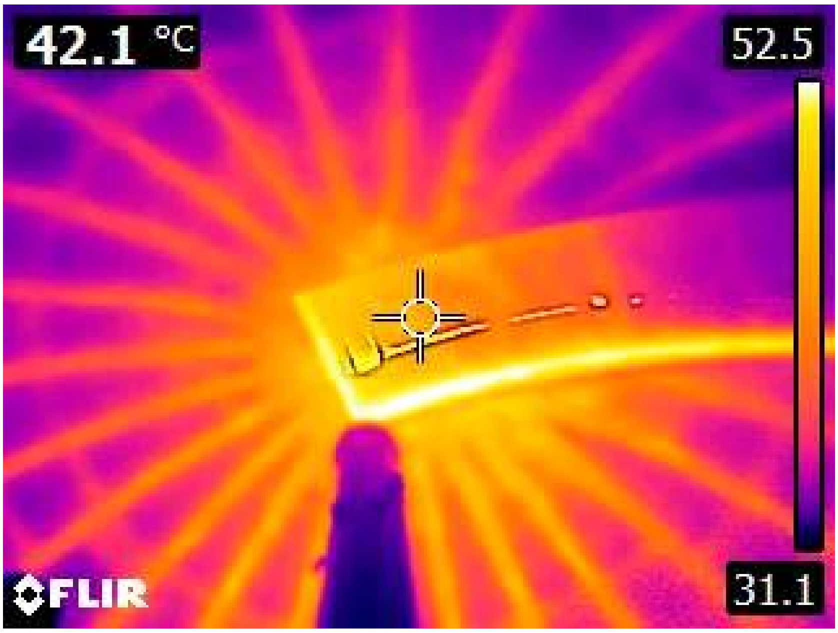


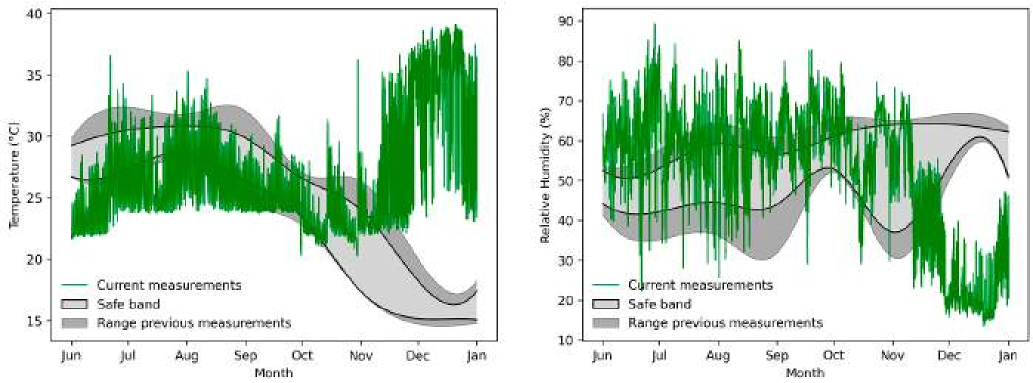
Figure 16. The surface temperature of the dome (T °C) detected with an infrared thermal camera in June 2023. The metallic ribs reach temperatures close to 53 °C, while the insulated panels show a temperature of around 30 °C. The thermogram was acquired using a FLIR E6xt infrared camera and processed through the FLIR Tools® Mobile app, version 2.6.0.215.

All these factors contribute to perturbing the climate of the Hall, threatening the preservation of the objects on display. Temperature and relative humidity variations may generate internal tension in the artefacts. They act in a cumulative way and, in the long run, cause the ageing of the materials and consequent decay of objects, especially those made of organic materials [16]. Although the Model was housed inside a display case, it was not sealed, leaving it vulnerable to external microclimatic fluctuations. This exposure caused physical responses in both the wooden substrate and the paint layers, which contract when losing moisture and expand when absorbing it. Over time, the cumulative effects of these dimensional changes became hazardous. The paint layers, only a few hundred nanometres thick (Figure 12) and mainly composed of gypsum and a proteinaceous adhesive (Figures 13a and 14), reacted more quickly to climate fluctuations than the wooden support, even those of short duration. As these layers aged, they lost elasticity and became increasingly vulnerable to mechanical stresses from both the substrate and external environmental variations. Consequently, the accumulation of minor changes, combined with abrupt damaging events, led to flaking and, in some cases, detachment of the paint layers [48–50].

As previously described, the Model experienced its most severe damage in late 2021, when a dangerous RH trend occurred due to excessive heating, pushing it beyond the safe limits of its historic climate.

Based on the EN 15757:2010 standard, the "safe zone" has been established, using the microclimatic data recorded in the 2013–2014 as a reference. This zone defines the safe range of temperature and relative humidity variability considered non-damaging to the hygroscopic materials based on their historic climate in the Merz Hall. Although RH constitutes the key variable, the association with T is useful for interpreting RH dynamics.

As shown in the graphs (Figure 17), in 2021, the parameters frequently exceeded the boundaries of the safe band, posing a significant risk to the displayed objects.



(**a**) (**b**)

Figure 17. Determination of the safe band for T (**a**) and for RH (**b**) as explained in the EN 15757:2010 standard.

The Model of Mars served as an early warning sign, highlighting the urgency of improving climate management in the Hall and of implementing effective mitigation strategies to prevent further damage.

Given that part of the collection cannot be relocated from Merz Hall without risking decontextualization, it is crucial to develop strategies that address the conservation challenges posed by the room's environment. A viable solution involves minimizing dependence on the air-conditioning system by leveraging the building's inherent thermal inertia. This may be achieved through a combined active and passive approach to microclimate control, which prioritizes the exploitation of the museum building's thermophysical properties, reserving the use of air-conditioning systems only for extreme scenarios to adjust parameters that fall outside the safe bands identified during the study.

In addition, the replacement of current display cases with climate-controlled models should be considered as an effective mitigation measure. This would offer localized protection for sensitive artefacts, shielding them from harmful environmental factors and enhancing long-term preservation efforts.

However, the issue of shielding against IR remains an open challenge due to the historic nature of the building, which limits the feasible solutions. While shielding solutions could help reduce IR impact, any intervention must respect the historical integrity of the space, further complicating the implementation of effective mitigation strategies. This challenge requires careful consideration to balance preservation needs with the limitations of working within a historical context.

Conservation Treatment of the Model

A conservation treatment was conducted at Merz Hall to minimize the Model's handling due to the fragile condition of the pictorial layers. The intervention, aimed to preserve the object's authenticity, involved the consolidation and re-adhesion of the pictorial layers.

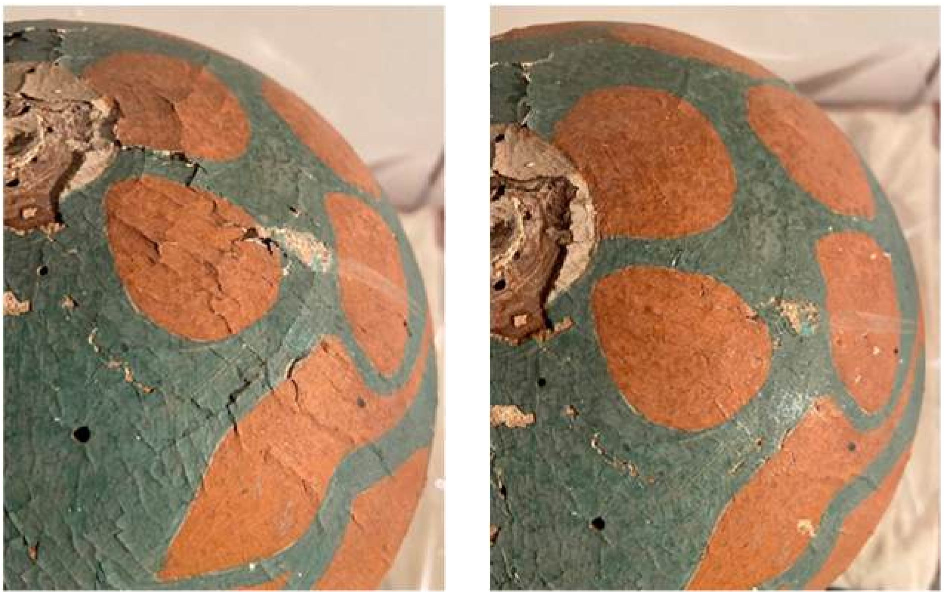
The task was particularly challenging due to the brittle, rigid, and fragile nature of the flakes, which made them prone to complete detachment.

Given the materials identified in the preliminary analysis, tests were conducted to select the most appropriate adhesive for the specific case, ensuring it would not stain, leave halos, or alter the optical properties of the surfaces to which it was spread [51].

A 3% solution of sturgeon glue in water provided the best results, allowing for the gradual softening of the more rigid paint film ridges and their perfect repositioning and re-adhesion. The glue was injected below the flakes by a syringe with a mesotherapy needle to ensure greater precision. To facilitate product penetration, ethyl alcohol was first injected into the areas to be treated. The complete re-adhesion of the layers was achieved by applying controlled heat and pressure using a flat-tipped thermocautery and a metal spatula, protecting the surfaces with a heat-resistant polyester film.

In areas with widespread flaking, the glue was applied by a brush, interposing a sheet of Japanese paper. After a few seconds, gentle pressure was applied to the area protected by the paper, using the brush bristles or cotton swabs, to promote the re-adhesion of the layers. Once the Japanese paper had been carefully removed, heat and pressure were applied with a spatula or thermocautery, protecting the painted surface with the heat-resistant polyester film [52–55].

These operations ensured the preservation of the object in its authenticity and saved all original paint fragments that had lost cohesion and adhesion (Figure 18a). Visible traces of a probable protective layer applied to the upper half of the Model (Figure 18b) were not removed on this occasion to allow for future analysis of the object and its conservation history.



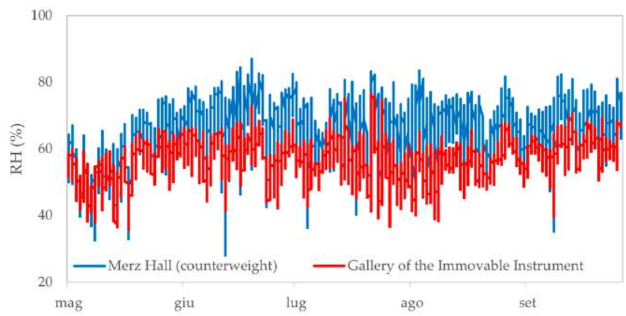
(a) (b)

Figure 18. The Model of Mars before consolidating the pictorial layers (**a**) and after the treatment (**b**).

Finally, a surface cleaning with a 2% solution of water and a non-ionic surfactant was performed on the painted wooden pedestal of the Model.

Once the pictorial film had stabilized, the Model was moved temporarily to a room of the museum (Figure 19a) with a more stable climate, where no significant RH peaks have been recorded in recent years (Figure 19b). In the next months, the Model of Mars will be placed inside a new climate-controlled display case to ensure appropriate temperature and relative humidity values for the long-term conservation of the object.

(**a**)



(**b**)

Figure 19. (**a**) Current location of the Model of Mars protected by the temporary display case in plexiglass in the Gallery of Immovable Instruments; (**b**) comparison of RH trends in the Merz Hall and the Gallery of Immovable Instruments in 2021.

6. Conclusions

The Model's deterioration has prompted a critical review of conservation policies at the Specola Museum, highlighting the urgent need for environmental improvements in exhibition areas.

It has clearly conveyed the risks associated with deviating from the historic climate regardless of the actual conditions and features in play to find an "ideal" climate based on standard indications.

Although the Model has been relocated, the risk of further deterioration phenomena involving other objects in the Merz Hall is expected to increase substantially if no actions are taken. The study of the Model of Mars has been an interesting case study for the significant conservation challenges posed by dome-shaped environments. These challenges are particularly relevant for historical institutions like the Specola Museum of Palermo, where instruments of significant heritage value must be protected within their original spaces. In such settings, architectural and environmental conditions are uniquely intertwined with the preservation of cultural heritage.

These conservation issues are shared with the other Italian historical astronomical observatories belonging to the National Institute for Astrophysics (INAF) which also safeguard a heritage of astronomical significance unique in the world, both in the number and value of the collections.

A survey conducted by the first author in 2024 through interviews with people in charge of cultural heritage conservation at INAF observatories regarding the use of dome-shaped rooms for heritage conservation revealed a varied situation. Some observatories successfully house historical instruments in their original dome-shaped rooms without significant conservation issues despite a lack of controlled environments. This is because the instruments are composed of materials (e.g., metals) that are not vulnerable to (modest) climate changes or variability, or because the historic climate of these rooms has not been significantly changed.

Conversely, other observatories have reported damage due to inadequate conservation conditions of the domes and their external coverings.

Additionally, while some observatories have excluded dome-shaped rooms from their exhibition pathways, others plan to use them for their scientific collections.

The presence of dome-shaped structures—originally designed for astronomical purposes—adds a unique layer of complexity to heritage conservation in INAF, emphasizing the need for a deep understanding of both the architectural and environmental contexts in which these objects are housed and the specific conservation challenges these unique architectural settings present. Such knowledge is crucial not only for the ongoing management of existing collections but also for the future planning of exhibitions, ensuring that conditions that could lead to catastrophic outcomes are avoided.

The Model of Mars's case emphasizes the profound impact that indoor climate management has on artefacts, underscoring the importance of assessing the risks associated with utilizing specific rooms for heritage conservation.

This study has further demonstrated that relying solely on poorly controlled air conditioning systems does not mitigate all climate-related risks and highlights the potential hazard of such an approach. At Specola Museum, efforts are underway to develop a combined active and passive climate management plan, focusing on maintaining safe thermo-hygrometric parameters identified during the presented study. This strategy aims to harmonize with local climate trends, ultimately achieving a sustainable collection management strategy that balances preservation needs with energy efficiency and cost-effectiveness while also minimizing the risks associated with active climate control system failures.

At the core of this plan is the continuous monitoring of both the artefacts and the physical variables that define the room's climate, which is essential for the real-time assessment and timely implementation of preventive measures.

The implementation of such strategies is now more crucial than ever in addressing the uncertainties surrounding the future of conservation, particularly in the face of climate change-induced risks.

The still-high degree of uncertainty in climate change simulations makes long-term monitoring necessary to better comprehend its effects on heritage conservation. Periodic maintenance, a preventive conservation plan informed by data from continuous monitoring, and an emergency risk assessment are imperative as climate change accelerates the decay of materials, triggers new forms of deterioration, and increases the risk of value loss [56]. This approach requires the involvement of experts across various fields: enhanced knowledge and collaborative efforts are crucial to mitigating the impacts of climate change on historical collections through adaptive or corrective actions.

Author Contributions: Conceptualization, M.R.C., I.C., F.P., A.d.V., and D.C.; methodology, M.R.C., I.C., F.P., A.d.V., and D.C.; software, M.R.C. and A.d.V.; validation, I.C., D.C., G.L., and G.C.; formal analysis, M.R.C., B.M., F.P., and A.d.V.; investigation, M.R.C., B.M., G.C., and G.L.; data curation, M.R.C.; writing—original draft preparation, M.R.C.; writing—review and editing, M.R.C., D.C., F.P., A.d.V., I.C., G.L., and G.C.; supervision, D.C., F.P., A.d.V., I.C., G.L., and G.C.; funding acquisition, I.C., G.L., and G.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the University of Palermo and the National Institute for Astrophysics (FFR-UNIPa).

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors upon request.

Acknowledgments: The authors would like to thank S.T.Art-Test di S. Schiavone & C for performing the radiographic analyses; Coniglio M., Martines F., Liggio G., Vitale G. and Speziale S. (INAF-OAPa), Agliolo Gallitto A. and Franzitta V. (UNIPa), Mirabello F. and Rodriguez Moreno A. for their support, collaboration and contribution to the study; Fazzio F. for the insightful advice on the conservation treatment for the Model and Di Stefano D. for sharing information about the restoration works conducted in the Sala dome during the 1990s.

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

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