# COSMIC-RAY EXPOSURE RECORDS AND ORIGINS OF METEORITES

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## ABSTRACT

The cosmic-ray records of meteorites can be used to infer much about their origins and recent histories. Some meteorites had simple cosmic-ray exposure histories, while others had complex exposure histories with their cosmogenic products made both before and after a collision in space. The methods used to interpret meteorites' cosmic-ray records, especially identifying simple or complex exposure histories, often are inadequate. Besides spallogenic radionuclides and stable nuclides, measurements of products that have location-sensitive production rates, such as the tracks of heavy cosmic-ray nuclei or neutron-capture nuclides, are very useful in accurately determining a meteorite's history. Samples from different, known locations of a meteorite help in studying the cosmic-ray record. Such extensive sets of meteorite measurements, plus theoretical modeling of complex histories, will improve our ability to predict the production of cosmogenic nuclides in meteorites, to distinguish simple and complex exposure histories, and to better determine exposure ages.

1. Introduction. Meteorites are fragments from a variety of objects in the solar system and can provide important information about these bodies. Well-determined cosmic-ray exposure histories are needed to help to establish the origins of meteorites: where they came from and how they were produced (1,2). In principle, the exposure history of a meteorite should be well determined if sufficient measurements are made of its cosmic-ray record and if the production rates and profiles of the cosmogenic products used to interpret the measurements are known well enough. It is unlikely that many meteorites have had their cosmic-ray exposure histories properly determined. Wetherill (3) noted that complex histories should be common for most likely meteorite-origin scenarios. However, complex histories for meteorites are seldom reported, especially for stony meteorites. Is this discrepancy between the predicted and reported frequencies of meteorite complex histories a problem with the approaches presently used to study the exposure records of meteorites? Inadequacies in the interpretation of the cosmic-ray records of meteorites could mean that exposure ages and other results of meteorite studies, such as cosmic-ray variations, also might not be correct. Systematic experimental and theoretical studies are needed to study how well we have been determining the recent histories of meteorites and to develop better methods for unfolding the cosmic-ray records of meteorites.

2. Cosmic-Ray Exposure Records. Among the ages of a meteorite, the youngest are those determined from the activities or concentrations of cosmogenic products. Exposure ages, the lengths of time that meteorites

have been exposed to cosmic rays, are typically orders of magnitude shorter than their radiometric formation ages and, for some meteorites, their brecciation ages and collisional shock ages (4). The cosmogenic products used to study exposure records of meteorites include stable and radioactive nuclides and tracks of heavy cosmic-ray nuclei. If a meteorite had a simple exposure record, then the concentration of a cosmogenic product and its production rate can be used to determine an exposure age. However, the production rates vary considerably with meteoroid size and shape and with sample location (5), so corrections for the effects of the sample's shielding geometry must be applied. Most methods for estimating shielding corrections, such as the Ne-22/Ne-21 or He-3/Ne-21 ratios, do not yield unique production rates but only narrow the range of possible values (5).

Many meteorites had simple exposure ages. Detailed investigations of the cosmic-ray records of several meteorites, such as the tracks, radionuclides, and spallogenic noble gases in St. Severin (6), show that the cosmogenic products were made only during one exposure geometry. However, most meteorites have not had their exposure records shown to have been simple by such systematic studies. Another clue that a meteorite probably had a simple history is that its exposure age is the same as a number of other meteorites of the same type. However, there are only a few clusters for the exposure ages of meteorites; the exposure ages for most meteorites form a continuous distribution.

The clusters of exposure ages for a given class of meteorites, such as the ~675 Ma (675 million years) cluster for IIIAB irons (7) or the ~6 Ma peak for H-chondrites (8), suggest that these meteorites were all produced by single, major collisional events. If these two clusters really represent individual events, the widths of the peaks, about 15-20% of the age, indicate that the sums of the uncertainties in determining cosmic-ray exposure ages are fairly large. As the measurement uncertainties are much smaller than 15-20%, the spread in the exposure ages for these clusters probably results from interpreting the measurements (although pre-irradiation or gas losses could account for some of the spread). One likely source of this width in the exposure-age peaks is the significant correction for shielding.

Several meteorites clearly had their cosmogenic products made both before and after a major collisional event in space that changed the meteoroid's geometry. The Jilin chondrite was irradiated by a significant flux of cosmic-ray particles for ~10 Ma near the surface of a very large object prior to its ejection ~0.4 Ma ago as an 85-cm-radius sphere (9). Several other meteorites have had complex histories, such as several inferred from the disagreements among exposure ages determined with different radionuclides or stable cosmogenic products. In very large meteorites, such as the Canyon Diablo iron meteorite (10), one part could have been removed by a minor collision without seriously affecting the formation of cosmogenic products in other parts of the meteoroid.

The distinction between simple and complex exposure histories can be difficult in some cases. Some meteorites probably have small amounts of cosmogenic products made prior to the event that produced the object that eventually hit the Earth. In most cases, the amounts of cosmogenic products made during the meteorite's final exposure geometry overwhelm any previous production. However, if this last exposure stage was short, then possibly the products made during the previous exposure could be detected. As suggested by (9), the high production rates inferred for Ne-21 from meteorites that have undersaturated Al-26 activities (that is, exposure ages of ~1 Ma) could be a consequence of pre-irradiation. A very special case of a complex history is when a foreign clast in a brecciated meteorite has had a previous exposure to the solar wind or cosmic rays prior to incorporation in the meteorite (11).

3. Systematic Experimental Studies. To properly calibrate the predicted production rates and profiles of cosmogenic products in meteorites, extensive sets of measurements are needed. The measurements should be made for samples from different, known locations and also of products with a wide range of production-rate-versus-depth profiles (tracks, high- and low-energy spallation, and neutron capture) and a variety of half-lives (including stable isotopes). For example, the Na-22 and Co-60 activities measured in Jilin (9) serve as a calibration points for cosmogenic nuclides in a meteoroid with a radius of 85 cm. The measurements of cosmogenic products in meteorite cores, such as those from St. Severin (6) and Keyes, also are valuable reference data.

However, few such well-characterized data sets for cosmogenic nuclides in meteorites exist (5). Most meteorites that have been investigated in detail have radii of ~10-40 cm, which are typical of most meteorites. There have not been many extensive studies of smaller meteorites. Laboratory irradiations of small spherical targets are helping to understand the production of cosmogenic nuclides in small meteoroids (12). While Jilin had a radius of 85 cm for its last 0.4 Ma, its initial exposure limits studies of cosmogenic nuclides in large spherical meteoroids mainly to short-lived radionuclides, such as Na-22 and Co-60. More detailed measurements are needed to calibrate the models used to predict the production rates and profiles of cosmogenic nuclides, especially for meteorites that had unusual preatmospheric sizes or shapes.

4. Theoretical Modeling. Calculated size- and depth-dependent production rates can be used to illustrate the use of a meteorite's cosmic-ray record to accurately unfold its exposure history. Most models do a fairly good job of reproducing the profiles of cosmogenic products in typical-sized meteorites, such as St. Severin (6). However, some models have trouble with very large meteoroids, like Jilin (9). Very small meteoroids are hard to model because the cascade of secondary particles, especially neutrons, is not fully developed (5,12) and solar-proton production is important. Improved models are needed for all sizes, shapes, and types (irons and stones) of meteorites.

Some of these model results have been used to study criteria for identifying complex histories. For example, the calculated track production rates and the Ne-22/Ne-21 ratios for meteorites with simple histories cover a small region of all possible values (13). Meteoritic samples with tracks and neon ratios that are outside this region have complex histories. The activities of cosmogenic radionuclides are often used in looking for complex histories, and often these activities versus track production rates or Ne-22/Ne-21 ratios are used to search for unusual exposure histories. Artificial exposure records derived from calculated production rates and profiles can be used to test the methods used to infer the exposure histories of meteorites. These theoretically constructed records for complex histories will especially help to show which features of a meteorite's cosmic-ray record are best suited for distinguishing complex from simple histories and which types of complex histories are most easily detected. Such theoretical studies would help to find the areas where meteorite measurements or more laboratory simulations or cross sections would be most useful.

5. Conclusions. Many experimental and theoretical studies are needed to improve our ability to unfold the cosmic-ray exposure records of meteorites. More extensive measurements of cosmogenic products in meteorites, especially shielding-sensitive ones like tracks and neutron-capture-produced nuclides, will help to identify meteorites that had complex histories and to yield better exposure ages. Such improved recent histories could aid in identifying the parent bodies for certain meteorites, such as primitive carbonaceous chondrites (possibly from cometary surfaces) or the SNC meteorites (the Shergottites, Nakhlites, and Chassigny, which were possibly ejected from the martian surface). Detailed measurements of cosmogenic products in meteorites could be used to improve the models for predicting the production rates of these products. Theoretical studies of the production systematics of cosmogenic products in meteorites will help to identify areas where additional laboratory or meteorite measurements are needed.

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