QUANTIFICATION OF THE HIGH EARLY SOLAR ACTIVITY USING COSMOGENIC NEON NUCLIDES IN METEORITIC MINERALS.

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Introduction: Astronomical observations have detected strongly variable, high-luminosity X-ray emissions from young stellar objects (YSOs) that provide evidence for high flare activity, with at least 10^5-fold enhancement in energetic protons compared to the present-day Sun [1]. The activity of YSOs consists of complex dynamic processes such as magnetic reconnection events that produce intense flares and release bursts of energetic charged particles (also known as solar cosmic rays, hereafter SCRs) and X-rays [2]. Meteoritic materials provide evidence for a highly active young Sun [3-7]. Excesses in the isotopes ^{6}Li, ^{7}Be, ^{10}Be, ^{41}Ca, ^{3}He, ^{21}Ne, and ^{50}V detected in meteoritic refractory minerals are attributed to spallogenic production from SCRs from energetic solar flares of the young Sun [3-8].The young Sun's SCR flux was estimated to be orders of magnitudes higher than today [7] but is otherwise poorly constrained and constitutes a missing piece in the history of the Sun [9]. Thus, a better estimate of the early solar activity is highly desirable.

Among the above SCR-produced nuclides, ^{21}Ne and ^{3}He are volatiles that can only be acquired after the formation of their host refractory minerals and could not have been inherited as a solar nebula or presolar gas [7]. SCR-produced Ne is more retentive in solids than He and has three stable isotopes that allow distinguishing cosmogenic Ne from other Ne components with different isotopic compositions and origins [7]. Thus, we choose cosmogenic Ne (hereafter Ne$_{\text{cos}}$) in the early solar system's most refractory minerals as a tracer for early solar activity. Here, we provide an improved estimate of the young Sun's SCRs flux with a new model that incorporates previously measured Ne$_{\text{cos}}$ produced within free-floating refractory minerals in the early solar system.

Method: To track the minerals' movement after they condensed close to the Sun and quantify their exposure to SCRs we apply both a particle movement model within a diffusive protoplanetary disk and a wind-driven ballistic ejection model for particles above the disk plane (see Fig. 1). To constrain the potential thermal loss of Ne through diffusion, we calculate the temperature profiles of refractory grains during transport in both models.

First, the "within the disk" model is built on previously developed particle tracking methods in a diffusive protoplanetary disk [10-12]. While most of the disk will be shielded from SCRs due to their relatively short penetration depths, as a result of the dynamic evolution of the disk, refractory grains can be stirred and lofted to significant height by turbulence in the disk, which is associated with mass and angular momentum transport. We investigate this process in the context of an early, active disk to evaluate the length of time grains reside in a location where they may be irradiated by SCRs and whether this exposure can explain what is recorded by the refractory grains.

Second, the "above the disk" model employs a simplified wind-driven ejection method which ballistically launches materials from near the Sun to fall back onto the disk at greater distances. Particles are released from their "launch area" close to the Sun when an outflow accelerates them to velocities of tens to hundreds of km per second upward and away from the star. Particles then move above the disk in a near-vacuum environment and get exposed to SCRs until they are accreted back onto the disk under the influence of gravity. We consider a range of launch velocities and angles and evaluate which conditions yield the necessary exposure and thermal histories to match the meteoritic record.

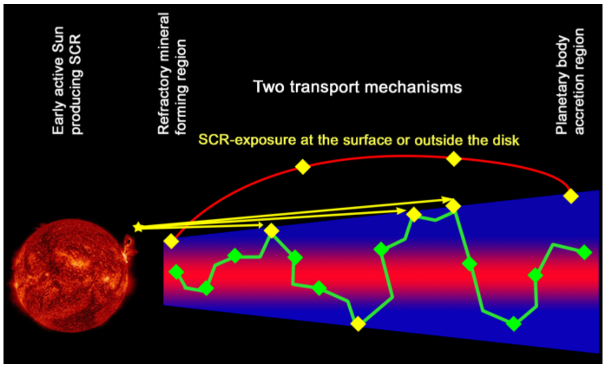

Fig. 1. Conceptual visualization of our two model approaches: Yellow diamonds indicate where SCR-irradiation occurred. The red curve represents the trajectory of a particle accelerated by the wind. The green curve represents the diffusive movement of a particle. Sun image courtesy of NASA.

Results & Discussion: (1) In the diffusion model, we track particles that are randomly placed in the refractory mineral-forming region for 10^5 years to over 10 AU. A representative trajectory of particles is shown in Fig. 2. While refractory grains may be lofted to heights that lead to exposure to SCRs, this region only makes up <0.1% of the total mass of the disk. As a result, very few grains are exposed, and those that are only see short durations of exposure, requiring unrealistically high particle fluxes to produce the record seen in refractory grains. Further, this would suggest that a large population of grains with no exposure should exist in the meteoritic record, and this is not seen [7]. (2) In the wind-driven model, particles are launched from the surface of the disk's inner edge. We focus on those trajectories where grains are reaccreted onto the disk (instead of lost to space) and re-enter the disk with minimal heating such that they would retain Ne. The effective exposure times (the nominal exposure to SCRs scaled to 1 AU heliocentric distance) of particles of interest are lower than 1 year with an average of 0.74 years (see Fig. 3). (3) Using the exposure times found here, we calculate that the observed concentration of $^{21}Ne_{cos}$ in refractory grains [7] requires a SCRs flux $10^{6.9}$ times higher than present day during the PLACs exposure and a flux $10^{5.6}$ times higher during SHIBs exposure.

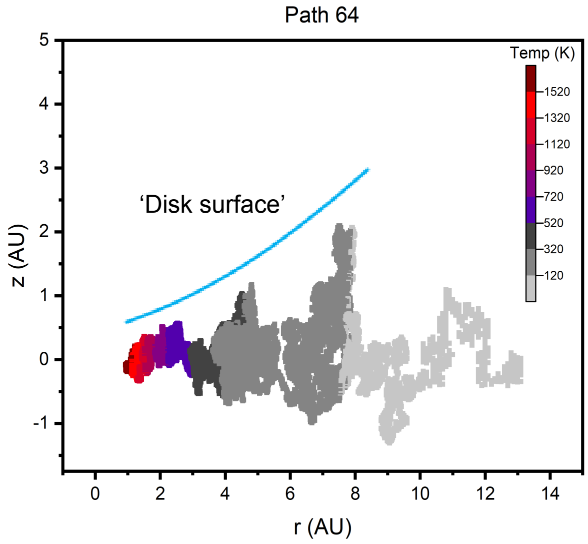

Fig. 2. One representative trajectory of particles in the solar disk. The y coordinate is the height above the midplane, and the x coordinate is the heliocentric distance. The grain temperature is indicated by color, and the disk surface is conceptually indicated by the blue curve.

Our model can also be used to interpret results from other useful and measurable cosmogenic nuclides such as beryllium-10 ($^{10}Be_{cos}$). Using the same parameters as for Ne our model estimates that the SCRs exposure of refractory minerals contributes to only 0.02% of the $^{10}Be_{cos}$ amounts, which suggests that the most ^{10}Be was inherited from their precursors, because in contrast to He and Ne, Be is a refractory element.

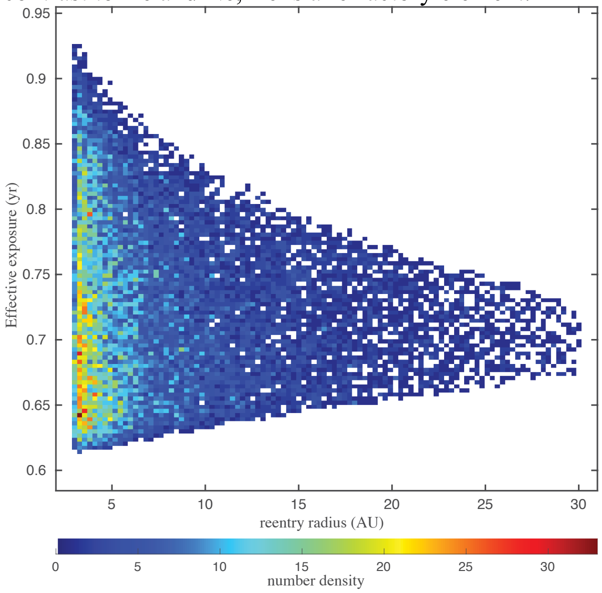

Fig. 3. Exposure time vs. reentry radius for refractory minerals reentering the disk with a low velocity and without heating. The color represents the number of particles per unit area (0.003 years and 0.27AU).

Assuming PLACs formed before SHIBs [7, 13] the higher SCRs flux during the PLAC exposure and lower flux during SCR exposure suggests a decreasing activity of the young Sun, consistent with astronomical observations of other YSOs [1, 14] that the earlier YSOs display tens of times higher activity than the later ones.

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