LATE INJECTION OF RADIONUCLIDES INTO SOLAR NEBULA ANALOGS IN ORION.
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Recent evidence for live ^{60}Fe in the early solar system [1,2] clearly indicates that the solar system formed near a supernova, in a region of high-mass star formation. Except for ^{10}Be, which has a separate, unique origin in galactic cosmic rays [3], it appears likely that many of the other short-lived radionuclides could be produced in their correct proportions in a type II supernova explosion. It is natural, then, to study proplyds (photoevaporating disks $\sim 10^3$ AU across [4]) and the smaller protoplanetary disks observed in the Orion Nebula [5] as analogs to our own solar system. These disks and proplyds tend to reside at small distances, $\sim$ a few $\times 10^{17}$ cm from the central stars of the Orion Nebula, especially the O6 star $\theta^1 \mathrm{Ori}\, C$ [4]. This $\sim 40\, M_\odot$ star will supernova in the next few Myr, and when it does, the solar nebula analogs in the Orion Nebula will lie in the path of the ejecta. This ejecta is sure to contain many of the short-lived radionuclides known to have been extant in the early solar system, including ^{26}Al, ^{60}Fe, ^{41}Ca, and ^{36}Cl [6]. In this abstract we assess the likelihood that protoplanetary disks in the Orion nebula could intercept and incorporate short-lived radionuclides from a nearby supernova. We consider the physical form in which the radionuclides exist, the trajectories taken by the ejecta, and the timing of their injection. We then compare our predictions to our own solar system to assess whether the solar system formed in an Orion-like setting.

The proplyds in Orion are disks that have already formed. Irradiation by the EUV and FUV fluxes from the central O stars, especially $\theta^1 \mathrm{Ori}\, C$, heats the gas in the disk to ~ 1000 K, causing the gas to expand and driving an outflow of neutral gas away from the disk. The hydrodynamics of this flow have been modeled and found to be in good agreement with observations [4]. The outflow extends outward for several hundred AU, and is characterized by densities $\rho \sim 10^{-19} - 10^{-18}\, \mathrm{g\, cm^{-3}}$. This stage lasts for several $\times 10^4$ yr to 1×10^5 yr, after which the disk has lost considerable mass due to evaporation.

If a nearby supernova explodes while the proplyd is still photoevaporating, the flow is hardly disturbed by the extra radiation. As in the case of SN1987A, UV fluxes typically drop in a year or less [7,8], and the flow quickly returns to its previous structure until the passage of the supernova shock. The timescale for the shock to reach the proplyd, using $2000\, \mathrm{km\, s^{-1}}$ from the supernova remnant Cas A as a typical ejecta velocity [9], is a few decades. When the ejecta strikes the proplyd, a shock is generated that penetrates deeper into the proplyd until a maximum density is reached, when the ram pressure behind the shock equals the gas pressure in the proplyd. For the energy budget of a supernova like Cas A (progenitor mass $\sim 15\, M_\odot$ [9]), and assuming an expansion of the supernova explosion to about 10^{17} cm, the ram pressure behind the shock is $\sim 0.3\, \mathrm{erg\, cm^{-3}}$. Thus the shock will penetrate until it reaches densities $\sim 3 \times 10^{-12}\, \mathrm{g\, cm^{-3}}$. Supernova shocks can propagate until they are very deep in the photoevaporative flow, stalling only when the almost reach the protoplanetary disk itself. For example, a disk with $\rho \approx 10^{-9}\, \mathrm{g\, cm^{-3}}$ at the midplane at 1 AU will have $\rho < 10^{-12}\, \mathrm{g\, cm^{-3}}$ only 1 AU above the disk, assuming a 0.1 AU scale height.

Radionuclides such as ^{26}Al and ^{60}Fe in supernova ejecta will condense out as dust grains of Al_2O_3, Fe_3O_3 $MgSiO_3$ and SiC, in a matter of months to a year in the case of SN1987A [10,11]. Presolar SiC grains associated with formation in supernova ejecta have been found in meteorites and their sizes tend to follow a log-normal distribution, centered on a radius $\sim 0.5\, \mu$m [12,13]

We have calculated the trajectories of these radionuclide bearing dust grains as the ejecta they are in collides with proplyds or protoplanetary disks. If the dust grains are in the leading edge of the ejecta, they will separate from the shock front as it begins to stall as it passes through the photoevaporative flow. We have modeled the density and velocity structure of the outflow according to [1], and we have calculated the drag forces and frictional heating of dust grains passing through it. We assume an initial dust velocity of $2000 \mathrm{km^{-1}\, s^{-1}}$. Table I shows the results for dust passing through an EUV-dominated outflow, indicating the radius of the dust particle,the peak temperature of the dust grain, and whether or not it successfully passed through the photoevaporative flow into the protoplanetary disk. From these results we see that a photoevaporative flow acts as a cushion, allowing supernova grains to enter the protoplanetary disk intact. Without this cushion, we find that radionuclide-

Table 1 *Dust injection in a PDR region*
r $\sim$ 250 AU, $\rho \sim 5 \times 10^{-19}$ g cm^{-3}

dust radius μm	Tmax K	injected?
10	250	yes
1	250	yes
0.1	250	no

bearing dust grains can penetrate the shock front, but then quickly evaporate as they encounter much denser gas on the other side. While such grains would not survive intact, they would nonetheless contribute their radionuclides to the protoplanetary disk. Given that the photoevaporating proplyd stage lasts for at most 10^5 years, while the lifetime of the Orion Nebula is $\sim$ 1 Myr, it is unlikely that a given disk will be photoevaporating when the supernova explodes. We view injection of radionuclides borne by dust grains as a likely event, but not without the destruction of those dust grains as they enter the protoplanetary disk.

We now consider the likely amounts of radioactivities that would be injected into a protoplanetary disk in Orion. The explosion of a $25\,M_\odot$ star in a type II supernova ejects about $7 \times 10^{-5}\,M_\odot$ of ^{26}Al [14], and the number of ^{26}Al atoms intercepted at a distance 10^{17} cm from the supernova would be about $5 \times 10^{16}\,(A/\mathrm{cm}^2)$, where A is the disk area. The solar system contains about $10^{18}\,(M/\mathrm{g})$ ^{27}Al atoms [15], where M is the disk mass. Taking the column density M/A at 3 AU to be $\sim 10^3\,\mathrm{g\,cm^{-3}}$ [16], we find a $^{26}\mathrm{Al}/^{27}\mathrm{Al}$ ratio $\sim 5\times10^{-5}$. We therefore conclude that it is reasonable for the solar system to have acquired its short-lived radionuclides in this fashion if it formed in an Orion-like setting. This scenario has the added advantage of providing a late injection of ^{26}Al into the solar system, explaining why FUN inclusions appear depleted in neutron-rich stable isotopes and in short-lived radionuclides like ^{26}Al [17]. One caveat is that the prompt injection (in $< 10^2$ yr) of radionuclides into the solar system does not allow ^{41}Ca time to decay, and would lead to an overabundance of ^{41}Ca in the early solar system [6]. This problem may be ameliorated, however, if the supernova ejecta was spatially highly inhomogenous, as is observed in the Cas A supernova remnant [9]. Nevertheless, simple integration of the initial mass function indicates that over 85 % of solar-type stars did form in environments like Orion, containing at least one star massive enough to supernova [18]. In future work we plan to further explore these issues in greater quantitative detail to assess whether our Sun was one of those 85 %, and whether it acquired its short-lived radionuclides by formation in proximity to a supernova.

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