

**THE UNLIKELY FORMATION OF THE SUN IN AN ORION-LIKE SETTING.** M. Gounelle<sup>1</sup>, A. Meibom<sup>1</sup> & P. Hennebelle<sup>2</sup>, <sup>1</sup>Laboratoire d'Étude de la Matière Extraterrestre, Muséum National d'Histoire Naturelle, 57 rue Cuvier, CP52, 75005 Paris, France. <sup>2</sup>Laboratoire de Radioastronomie Millimétrique, École Normale Supérieure et Observatoire de Paris, 24 rue Lhomond, 75231 Paris Cedex 05, France (gounelle@mnhn.fr).

**Introduction:** Short-lived radionuclides (SRs) are radioactive elements with half-lives of  $\sim 1$  Myr. Some SRs were present in the protoplanetary disk at abundances substantially higher than the levels expected for average interstellar medium [1]. Those SRs therefore require a last minute origin [1], such as injection in the protoplanetary disk by a nearby supernova (SN) [2] or *in situ* irradiation of the disk solids [3]. The origin of SRs is highly debated, because it has important consequences for early solar system chronology, planetesimal heating and the astrophysical environment in which our solar system was born.

In the nearby SN scenario, it is assumed that the massive star, which evolved into a SN, and our protoplanetary disk were coeval, and formed in the same stellar cluster [4]. The SN injection model therefore implies that our Sun was born in a large stellar cluster such as the Orion Nebula Cluster (ONC). Such a scenario needs to satisfy at least 3 basic requirements.

(1) The receiving protoplanetary disk has to lie in a narrow enrichment zone relative to the SN to receive the correct amount of SRs without being disrupted by the SN ejecta. Ouellette et al. [2] estimate this enrichment zone to be between 0.1 and 0.4 pc from the massive star. (2) Even the most massive stars need a few Myr to explode in a SN. As SRs were present in the earliest phases of the disk ( $< 1$  Myr), this strongly constrains the co-evolution of the massive star and the disk. (3) The receiving disk belongs to the fraction of disks which survived the severe photoevaporation due to the massive star enhanced UV flux [5].

At the conference, we will (1) present general astronomical arguments which strongly disfavour an ONC-like setting and, (2) estimate the probability that *any* star in the Galaxy receives SRs from a nearby SN at the levels inferred for our solar system, taking into account the 3 constraints enounced above. Because the calculated probability is very low, we will (3) propose an alternative origin for SRs, focusing on  $^{60}\text{Fe}$ , usually taken as a proof of an ONC-like setting.

**The unlikely ONC-like setting:** In the ONC, the most massive object is the  $40 M_{\odot}$  star,  $\theta^1 C$  Ori, which will go SN in  $\sim 5$  Myr. The age of the ONC is  $< 1$  Myr,  $\theta^1 C$  Ori being among its youngest members [6].  $\theta^1 C$  Ori will therefore go SN in  $\sim 4$  Myr, 5 Myr after the onset of star formation in the ONC.

The protoplanetary disks that are currently within a few tenths of a parsec from  $\theta^1 C$  Ori will suffer severe

mass-loss due to photoevaporation driven by the UV radiation from this and other massive stars in the region [7]. With photoevaporation mass loss rates of  $\sim 10^{-7} M_{\odot}/\text{yr}$ , the typical lifetime of a minimum solar mass nebula of mass  $0.01 M_{\odot}$  is therefore  $\sim 10^5$  yr. Johnstone et al. [7] studied the specific case of  $\theta^1 C$  Ori and showed that, at a distance of 0.3 pc, a protoplanetary disk would shrink to a size of about 1 AU in about 1 Myr, i.e. well before  $\theta^1 C$  Ori becomes a SN. Disk evaporation simply prevents injection of SN ejecta because disks in the vicinity of the SN have essentially disappeared before the SN explosion takes place.

Even if disks adjacent to  $\theta^1 C$  Ori survived photoevaporation, in 4 Myr from now, such surviving disks will be highly evolved, harboring large planetesimals as well as giant planets. Disks which survive evaporation will therefore not receive SRs from the SN explosion until very late in their evolution, inconsistent with cosmochemical evidence for early delivery, which indicates that the injection happened within 1 Myr of disk formation [1].

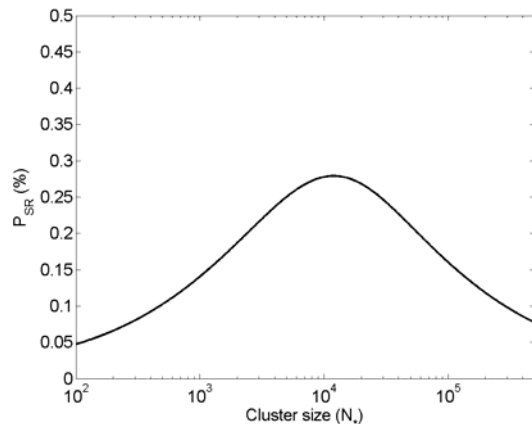
Over the next 4 million years, there will be few new stars forming within 1 pc of  $\theta^1 C$  Ori. Star formation is more vigorous during the first Myr of a molecular cloud lifetime and decreases sharply with time [8]. The decrease with time of the star forming rate is even more dramatic in the immediate vicinity of a massive star ( $< \text{few pc}$ ) than at the global molecular cloud scale. Star formation cannot occur in the absence of molecular gas, which is dissipated by the strong winds and ionization power of massive stars. Wren & O'Dell [9] estimate that the HII region created by  $\theta^1 C$  Ori is now 0.3 pc wide and is growing at the rate of 0.5 km/s. Within the next 4 Myr, this region will expand to a  $\sim 2.3$  pc wide HII cavity around  $\theta^1 C$  Ori, where star formation will be effectively halted. Hillenbrand [10] estimates that the gaseous region surrounding  $\theta^1 C$  Ori will be photoevaporated on a timescale of  $< 1$  Myr.

After a few Myr of evolution, star formation in ONC-like settings occurs mainly in photo-dissociation regions (PDRs) at the interface of the HII region and the molecular gas, at a few parsecs from the massive star. The fate of the ONC is well illustrated by the 2-3 Myr old NGC2244 cluster, whose most massive star, HD206267, has the same spectral type as  $\theta^1 C$  Ori. In NGC2244, star formation is occurring in the outskirts of the cluster, at distances 5-10 pc from the central O6

star [11]. In addition, Reach et al. [12] note that these stars, which formed  $\sim 2$  Myr before HD206267 goes supernova are the last generation of stars forming in the cluster. Low-mass stars which formed 3 Myr after the onset of star formation are too far away from the SN to be contaminated by SRs at any significant level.

#### Probability of disk pollution by a nearby SN:

The probability for a young disk ( $< 1$  Myr) to be contaminated in SRs by a nearby supernova explosion at the level observed in the early solar system depend on the fraction of young low-mass stars present in the cluster at the time of the SN explosion, on the fraction of low-mass stars present in the enrichment zone and on the fraction of protoplanetary disks which survived UV photoevaporation. Adopting conservative numbers for the fraction of disks present in the enrichment zone and surviving evaporation, we obtain the variation of the injection probability of a disk by a nearby SN as a function of the cluster size  $N_*$  (Figure 1). It reaches a peak value of 0.3 % for a cluster size of 10000 stars.



The probability for *any* star in the Galaxy to have its young disk contaminated in SRs from a nearby SN explosion at the level observed in the solar system is calculated by integrating the curve shown in Figure 1 with the cluster size distribution [14]. It amounts to 0.1 %. If multiple supernovae are taken into account, the probability reaches a maximum value of a few %. This number is lower than the number calculated by [13] who do not take into account photoevaporation.

**Radioactive molecular clouds:** The injection of SRs by a nearby SN is an unlikely event. Although improbable does not mean impossible, this very low probability suggests that other sources should be considered for explaining the overabundance (compared to the interstellar medium average value) of SRs in the early solar system [1]. Some of the SRs, such as  $^{26}\text{Al}$ ,  $^{36}\text{Cl}$ ,  $^{41}\text{Ca}$  and  $^{53}\text{Mn}$  can be made by in situ irradiation together with  $^{7,10}\text{Be}$  [3], and therefore do not necessitate further elucidation.  $^{60}\text{Fe}$  on the other hand cannot be made by irradiation [15]. It is therefore key to find a

source of  $^{60}\text{Fe}$ , within a plausible astrophysical context.

The most recent theories on molecular cloud (MC) formation suggest that a significant fraction of these form from the collision of turbulent flows which compress the interstellar gas and provoke the atomic to molecular transition [16]. Such flows are most likely created by SN explosions [17]. In these models, relatively high concentrations of  $^{60}\text{Fe}$  and other SRs are expected in MCs. This is because massive stars winds and SN ejecta whose compression effects build MCs *also* carry large amount of SRs [18]. Because MCs form in  $\sim 5$ -10 Myr [16], they will contain only SRs which have half-lives larger than  $\sim 1$  Myr.

To test this idea, we have performed 3D numerical simulations using the RAMSES-MHD code [19]. The code solves the MHD equations using Godunov-type methods and include self-gravity. The simulations deal with a cloud of interstellar atomic gas assembled by a converging flow of warm neutral gas which provokes the formation of cold neutral gas [17, 20, 21]. Once enough cold gas has been formed, gravity takes over and the system reaches a state similar to those of observed MCs. Passively advected particles representing  $^{60}\text{Fe}$  nuclei are introduced in the simulation at a time corresponding to a SN explosion with abundances given by SN nucleosynthetic models [18]. Systematic investigations of the parameter space will allow us to specify under which circumstances the average abundance of  $^{60}\text{Fe}$  in the MC is compatible with that observed in early solar system.

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