ALUMINIUM-26 IN THE EARLY SOLAR SYSTEM : A PROBABILITY ESTIMATE.

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Introduction: While more and more planetary systems are discovered around Sun-like stars, it is important to know how likely was the formation of the Sun. The orbital elements of the giant planets and the Kuiper belt as well as the presence of short-lived radionuclides (SLRs), such as ^{26}Al ($T_{1/2}$ = 0.72 Myr) and ^{60}Fe ($T_{1/2}$ = 2.6 Myr) in the early Solar System [1] have helped for some time to answer that important question [2]. Because in a large cluster dynamical encounters are more frequent and disruptive than in a small one, the dynamically cold orbital distribution of giant planets and the mere existence of the distant Kuiper belt have been used to give an upper limit to the size of the Sun's parent cluster. SLRs in the Solar System have long been thought to have been injected into the solar dense core or protoplanetary disk by a nearby (< 1 pc) supernova (SN) [3-5]. Because SN progenitors are more numerous in large clusters than in small ones, their presence in the nascent Solar System was used to give a lower limit to the size of its parent cluster. Recent findings have however relaxed these long-standing constraints. The goal of the present work is to reassess the likelihood of formation of a star-planet system similar to our Sun.

New constraints: Based on new observational estimates of clusters' lifetimes and densities, [6] showed that the dynamical properties of the Solar System are not incompatible with its birth in a large cluster. It has been argued that the presence of a SN within a parsec of a protoplanetary disk or a dense core is at odds with star formation mechanisms [7, 8]. In addition, SNe overproduce ^{60}Fe relative to ^{26}Al and their respective Solar System initial abundances [9]. Finally, the ^{60}Fe Solar System initial abundance estimate has been decreased by a factor > 10 [10, 11]. These observations lead to three important conclusions: (i) ^{60}Fe in the nascent Solar System did not originate from a single nearby SN but from a set of SNe which exploded many Myr before the Solar System formation [12], (ii) the SNe which delivered ^{60}Fe were not the source of the solar ^{26}Al, (iii) ^{26}Al presence in the early Solar System is now the best (only) way to constrain the likelihood of the astrophysical context of our Sun's birth.

Aluminium-26 origin: While ^{60}Fe is delivered into the interstellar medium (ISM) by SNe only, both SNe and massive star winds contribute to the ISM inventory of ^{26}Al [13]. [14] and [15] have examined the possibility that the ^{26}Al–rich wind from a single (runaway) Wolf-Rayet (WR) star contaminated the nascent Solar System. Because WR stars are very rare and soon followed by a SN explosion leading to an excess of ^{60}Fe, these models do not apply to the Solar System.

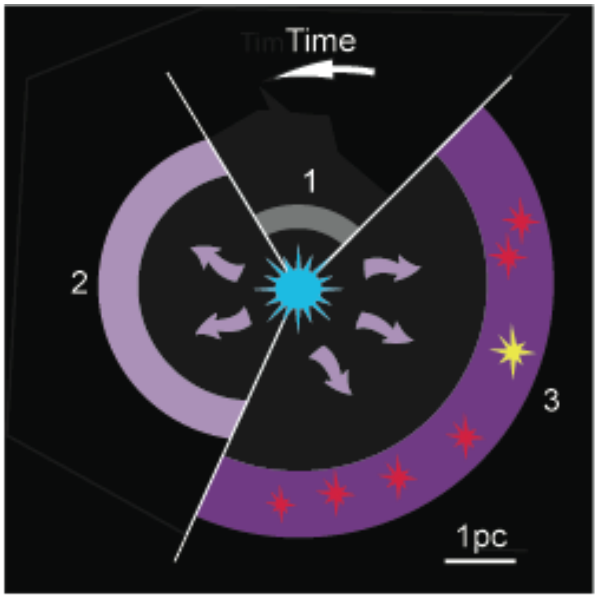

Fig 1: Incorporation of ^{26}Al in a dense shell created by a massive star wind. Phases 1 & 2 correspond to the collection of interstellar gas and injection of ^{26}Al by the wind (arrows). Phase 3 corresponds to the gravitational collapse of the shell and the formation of a new, ^{26}Al-rich, star generation including the Sun (yellow). The whole process lasts a few Myr (see text).

[16] proposed instead that ^{26}Al was injected in a dense shell of mass ≈ 1000 $M_\odot$ collected by a massive star wind (Fig. 1). Because rotating massive stars models are used, injection in the shell starts as early as the entry of the star into the main sequence, lasts for some Myr and ends well before the SN explosion. When the collected shell has become dense enough and gravitationally unstable, it collapses and a second generation of stars form which contain ^{26}Al. Detailed calculations have shown that as long as the parent star, baptized *Coatlicue*, is more massive than M_{min} = 32 $M_\odot$, the abundance of ^{26}Al in the shell is equal or larger than that of the Solar System, depending on the mixing efficiency of the wind material with the shell. This model is in line with observations of induced star-formation within dense shells around massive stars [17].

Probability estimate: In the framework of that model, it is possible to identify the most likely parent cluster size in introducing two constraints : (i) the cluster to which *Coatlicue* belonged contained at least one star more massive than $M_{min} = 32\ M_{\odot}$ (see above), and (ii) it contained less than $n_B = 5$ stars more massive than $M_{SN} = 8\ M_{\odot}$, in order to prevent the formation of a superbubble [18] which would have caused ^{26}Al leaking rather than accumulation into the shell.

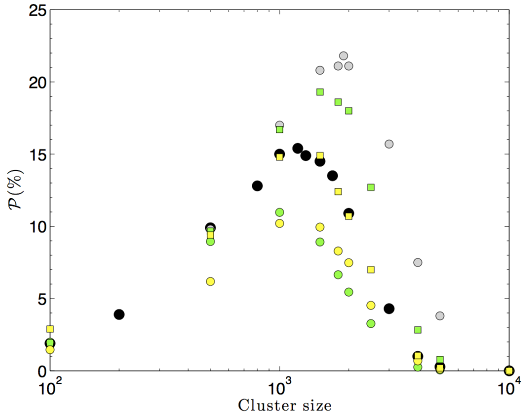

Fig 2: Probability for a cluster to satisfy the dual condition necessary for a massive star to inject ^{26}Al at the solar abundance into a collected dense shell (see text). The black curve is the result obtained with fiducial parameters, while other curves are obtained in varying the parameters M_{min}, n_B and M_{SN} (see text).

Simulating the stellar initial mass function (IMF) in a Monte-Carlo fashion [19], it is possible to calculate the probability density to realize that double condition as a function of the parent cluster size (Fig. 2). There is a distinct peak for a parent cluster size $N \approx 1200$. If calculation parameters (such as M_{min}, n_B, M_{SN}) are set to vary, the value of the peak does not change much and remains within the range of 1000-2000 stars (Fig. 2).

It is possible to calculate the fraction of clusters which realize that double condition using the number distribution dN/dM of stellar clusters, which has been estimated by several workers to vary as N^{-2} for clusters' sizes from $N_{min} = 10^2$ to $N_{max} = 5 \times 10^5$ [7, 20]. Using the fiducial probability distribution depicted with black circles in Fig. 2, a total cluster fraction of 5.2 % is calculated. Exploring the whole range of curves shown in Fig. 2, the total cluster fraction varies between 3.5 and 5.8 %. Though this is not stricto sensu the probability of formation of a star containing ^{26}Al at the solar value, this fraction tells us that 5 % of all clusters offer a favorable setting for producing second generation ^{26}Al-bearing stars (and planets). Each of these clusters will produce hundreds of ^{26}Al-rich low-mass stars (and planets).

Discussion: One percent or so is a relatively high number. It means that, though not the rule, the presence of ^{26}Al in planetary systems is not at all an exception. It corresponds to the observation that triggered star formation is a common and generic mode of star formation [21]. It is comparable to the probability estimate calculated by [7, 8] for injection by a single SN. These works however vastly surestimated the fraction of disks (or cores) present within 1 pc of a SN. In fact, when massive stars are ready to explode as SNe, they are surrounded by HII regions of radius a few pc where star formation does not occur [21]. If that constraint had been taken into account by [7, 8], the probability estimate for a single SN would have been close to zero.

The number of a few % is in contradiction with [22] claiming that ^{26}Al is a common feature of planetary systems. According to [22], white dwarves chemical composition imply that these stars have swallowed differentiated asteroids. The observed variations of the white dwarves Fe/Al could however be due to a non solar composition or to contamination by planets rather than asteroids (not requiring ^{26}Al as a heat source).

Conclusions: The recently identified mechanism accounting for ^{26}Al presence in the early Solar System corresponds to a common astrophysical setting (few %). The relatively high probability to form a planetary system rich in ^{26}Al has important implications for the habitability of other worlds [23]. The presence of a massive star at a few pc (rather than at a tenth of a pc) might have positively influenced disk dissipation and planetary formation [24].

References: [1] S.S. Russell, et al., *Phil. Trans. Roy. Soc. A* 359 (2001) 1991. [2] F.C. Adams, *ARAA* 48 (2010) 47. [3] A.G.W. Cameron & J.W. Truran, *Icarus* 30 (1977) 447. [4] N. Ouellette, et al., *ApJ* 662 (2007) 1268. [5] A.P. Boss, et al., *ApJ* 708 (2010) 1568. [6] D. Dukes & M.R. Krumholz, *ApJ* 754 (2012) 56. [7] J.P. Williams & E. Gaidos, *ApJ* 663 (2007) L33. [8] M. Gounelle & A. Meibom, *ApJ* 680 (2008) 781. [9] S.E. Woosley & A. Heger, *Physics Reports* 442 (2007) 269. [10] F. Moynier, et al., *ApJ* 741 (2011) 71. [11] H. Tang & N. Dauphas, *EPSL* 359 (2012) 248. [12] M. Gounelle, et al., *ApJ* 694 (2009) L1. [13] R. Diehl, et al., *Nature* 439 (2006) 45. [14] M. Arnould, et al., *A&A* 321 (1997) 452. [15] V. Tatischeff, et al., *ApJ* 714 (2010) L26. [16] M. Gounelle & G. Meynet, *A&A* 545 (2012) A4. [17] L. Deharveng, et al., *A&A* 523 (2010) A6. [18] J.C. Higdon & R.E. Lingenfelter, *ApJ* 628 (2005) 738. [19] P. Kroupa, et al., *MNRAS* 262 (1993) 545. [20] C.J. Lada & E.A. Lada, *ARAA* 41 (2003) 57. [21] P. Hennebelle, et al., in: Structure Formation in Astrophysics, G. Chabrier, Ed., Cambridge University Press, Cambridge, 2009, pp. 205. [22] M. Jura, et al., *ApJ* 775 (2013) L41. [23] I. Gilmour & C.A. Middleton, *Icarus* 201 (2009) 821. [24] H.B. Throop & J. Bally, *ApJ* 623 (2005) L149.