

# Circumstellar disks in high-mass star environments: the early solar system

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**Abstract.** The early solar system represents the only case we have of a circumstellar disk that can be investigated “in situ” -albeit 4.6 Gyr after its formation. Meteorites studies give mounting evidence for an intense irradiation phase of the young circumsolar disk by energetic particles, and also for contamination by products of high-mass stellar and/or explosive nucleosynthesis. We thus discuss the conditions of the birth of the solar system in a high-mass star environment.

**Keywords.** early solar system, meteorites, nucleosynthesis, massive stars

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The very early stages of the formation of the solar system took place while the young Sun was still surrounded by a circumstellar disk, some 4.6 Gyr ago. Although the growth from micron-sized particles (dust grains) to km-sized bodies (“planetesimals”) remains a major unsolved problem in planet formation theory, collisions between small, undifferentiated bodies are still ongoing, and generate debris in the form of meteorites known today as “carbonaceous chondrites”, that contain the earliest solids of the solar system.

The composition of these primitive meteorites is generally similar to the so-called “cosmic abundances”, with a few important exceptions (see Lauretta & McSween 2006). They contain “calcium-aluminium-rich inclusions” (“CAIs”), which show an excess of elements that are the daughter products of the decay of radioactive isotopes with periods on the order of 1 Myr or less. These are the so-called “extinct radioactivities” (because the elements have long completely disappeared), or “short-lived radioactivities” (“SLRs”). The parent-daughter pairs and half-lives are:  ${}^7\text{Be} \rightarrow {}^7\text{Li}$  (52 days);  ${}^{41}\text{Ca} \rightarrow {}^{41}\text{K}$  (0.1 Myr);  ${}^{36}\text{Cl} \rightarrow {}^{36}\text{S}$  (0.3 Myr);  ${}^{26}\text{Al} \rightarrow {}^{26}\text{Mg}$  (0.74 Myr);  ${}^{10}\text{B} \rightarrow {}^{10}\text{Be}$  (1.5 Myr);  ${}^{60}\text{Fe} \rightarrow {}^{60}\text{Ni}$  (2.7 Myr). Primitive chondrites also contain longer-lived isotopes, but their abundances are expected as a “cosmic background” of stellar nucleosynthesis in our galaxy.

In contrast, the SLRs testify to the nucleosynthetic processes that took place within a Myr or so of the birth of the Sun and the solar system. Two isotopes bear unequivocal signature of their formation processes:  ${}^7\text{Be}$  and  ${}^{10}\text{Be}$  cannot be coming from stars (since they are easily burned in their interiors) but are efficiently formed in “spallation reactions” (= in-flight nuclear reactions); in contrast, the heavy, neutron-rich nucleus  ${}^{60}\text{Fe}$  can only be produced in supernova explosions. The other nuclei in between can, to varying degrees, be produced by either spallation reactions, or massive star nucleosynthesis, or a combination of both, in particular  ${}^{26}\text{Al}$ . How is this possible ?

Young low-mass stars are *all* seen flaring in X-rays. Studies of hundreds of these stars have shown that their X-ray flares are associated with solar-like *magnetic activity*, enhanced by 3-4 orders of magnitude compared to the Sun ( $L_X/L_{bol} \sim 10^{-4} - 10^{-3}$ ; e.g., Güdel 2004). Therefore, it is very reasonable to assume that, as is the case for solar flares, all young, low-mass stars accelerate particles in flares (notably protons,  ${}^3\text{He}$  and  $\alpha$ -particles), and are thus able to generate spallation reactions with the surrounding material -here dust grains (containing Si, C, O, Mg, etc.) in circumstellar disks. Along

those lines, it has been shown that not only  $^7\text{Be}$  and  $^{10}\text{Be}$ , but also all the other SLRs (excluding  $^{60}\text{Fe}$ ) could be produced, within factors 2-3, by this single *generic* mechanism (e.g. Gounelle *et al.* 2006) -the young solar system thus being no exception.

However, low-mass stars can be formed either in loose clusters like Taurus-Auriga, or in “OB associations” of up to several thousand stars. If they are massive enough, the brightest stars turn supernova (hence contaminate their surroundings with the  $^{60}\text{Fe}$  synthesized during the explosion) in only a few million years, i.e., while the associated low-mass stars may still possess dense circumstellar disks. Taking a disk *e*-folding lifetime of  $\sim 1 - 2$  Myr (Cieza *et al.* 2007) puts a lower-limit of over  $\sim 100M_{\odot}$  to the mass of the exploding star. Therefore, it is logical to infer that, because  $^{60}\text{Fe}$  was trapped in carbonaceous chondrites within  $\sim 1$  Myr of the formation of the solar system, (*i*) a supernova from a very massive star exploded in its vicinity, (*ii*) the Sun was born in a rich OB association, such as the present-day Orion Nebula Cluster. However, one finds that such a “cosmic coincidence” is extremely unlikely (probability of a few percent at most, more likely  $< 0.1\%$ ) (Williams & Gaidos 2007, Gounelle & Meibom 2008). The implication here would be that the Sun must have been born in a fairly exceptional environment. Note that the strong winds characteristic of massive stars before they explode can spread freshly synthesized  $^{26}\text{Al}$ , after a time delay of  $\gtrsim 1 - 2$  Myr to lift it from the stellar interior into the outer wind radiative acceleration zone (see Voss *et al.* 2009).

The above conclusion, however, rests on the assumption that the exploding massive star and the surrounding low-mass stars are more or less *coeval*. But it has long been known that star formation in OB associations takes place in successive bursts triggered by SN explosions. As a consequence, a given low-mass star may be born as a *second generation* and be exposed to the explosion of a first-generation massive star. A modern version of the “SN-triggered star-formation scenario” has been subject to extensive numerical simulations. In the so-called “turbulent convergent flow” model (see Hennebelle *et al.* 2007), molecular clouds form because they are compressed by stochastic SN explosions, hence can be contaminated by nucleosynthetic products like  $^{26}\text{Al}$  and  $^{60}\text{Fe}$ , and give birth to new stars. Little  $^{26}\text{Al}$  will be left because of its short 0.73 Myr half-life, but  $^{60}\text{Fe}$ , with its 2.7 Myr half-life, will not have decayed as significantly (Gounelle *et al.* 2009).

We conclude that our own circumstellar disk, that preceded the formation of the solar system, was subject to a series of events that could be of general relevance: (*i*) like all low-mass young stars, the flaring young Sun irradiated its inner circumsolar disk, and left traces of this irradiation in the form of radioactive Be isotopes and possibly heavier SLRs; (*ii*) the Sun was born in a massive-star environment:  $^{60}\text{Fe}$  is likely due to explosions of massive stars of previous generation(s);  $^{26}\text{Al}$  may be a combination of flare-induced spallation reactions and contamination by winds of massive stars of the same association, before these coeval stars explode as SN, too late to contaminate its disk.

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