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Massive stars: privileged sources of cosmic-rays for interstellar astrochemistry

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Abstract: Massive stars can be considered as crucial engines for interstellar physics. They are indeed the main providers of UV radiation field, and constitute a substantial source of chemical enrichment. On their evolution time-scale (at most about 10 Myr), they typically stay close to their formation site, i.e. close to molecular clouds very rich in interstellar molecules. These stellar objects have also the property to be involved in particle acceleration processes leading to the production of high energy charged particles (cosmic-rays). After rejection in the interstellar medium, these particles will play a substantial role in processes such as those simulated in various facilities dedicated to experimental astrochemistry. This short contribution intends to put these particles, crucial for astrochemistry, in their adequate astrophysical context.

1 Introduction

The chemistry of molecular clouds is very rich (see e.g. Ehrenfreund & Charnley 2000, Tielens 2005, Herbst & van Dishoeck 2009, De Becker 2013). These interstellar clouds are populated by many species, ranging from the smallest molecules up the more extended polycyclic aromatic hydrocarbons (PAHs). These molecular populations contain representatives of many classes of compounds, including organic species whose properties are rich enough to envisage the presence of – still undetected – amino acids in the interstellar medium. Such a rich interstellar chemistry, despite the low densities and low temperature of molecular clouds, requires notably an input of energy. However, the radiation fields from neighboring stars are not able to reach the core of these clouds. In this context, one should emphasize the significant role played by high energy charged particles, the so-called cosmic-rays (see e.g. Cravens & Dalgarno 1978, Prasad & Tarafdar 1983, Yeghikyan 2011). As a result of their rather low cross section with species present in the interstellar medium, cosmic-rays are not stopped by the outer layers of molecular clouds. They can therefore disseminate at least a small fraction of their energy even in the core of these clouds, which can not be reached by stellar photons produced in the neighbourhood.

In this context, it is relevant to put these important particles in their adequate scientific context, emphasizing for instance the important role of massive stars in the phyciso-chemistry of the interstellar medium (see De Becker 2014 for a review). In a few words, massive stars are the brightest stellar objects in the Galaxy. They are the main providers of UV radiation, and they produce strong stellar

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winds powered by radiation pressure (e.g. Puls et al. 2008). These stellar winds are able to eject in the interstellar medium amounts of stellar material ranging between 10^{-7} to 10^{-5} solar masses per year, with wind velocities ranging typically between 1000 and 3000 km s^{-1} (see e.g. Crowther 2007, Muijres et al. 2012). In addition, when the nuclear fuel available in their core is exhausted, their evolution ends with the supernova event, responsible for a substantial ejection of material in the interstellar medium (Chevalier 1977, Georgy et al. 2009).

It is important to emphasize that the outflows of material in relation with massive stars (stellar winds, supernovae...) are likely to produce strong hydrodynamic shocks. These astrophysical shocks are known to be sites of efficient particle acceleration processes (Diffusive Shock Acceleration, DSA), responsible for the production of significant amounts of cosmic rays (Fermi 1949, Bell 1978). These high energy particles consist mainly of electrons, protons, helium cations, and higher mass ions, with energies up to a few 100 TeVs (as far as Galactic cosmic-rays are concerned). The energy spectrum of particles accelerated by the DSA mechanism is known to be a power law, with a negative index: even though quite high energies can be reached, the bulk of the high energy particles have energies below MeVs. The role of massive stars in particle acceleration processes, and their proximity with respect to molecular clouds allow to express the idea that they certainly constitute the main providers of cosmic-rays at work in astrochemical processes.

In the context of experimental astrochemical studies, the investigation of the interaction of high energy charged particles with molecular species to simulate astrophysical conditions deserves to be introduced in its relevant context. This short contribution aims at providing a connection between the physico-chemistry of some processes studied in experimental astrochemistry and the astrophysical environments where they should be operating. The issue of the production of cosmic-rays is briefly discussed in Section 2 with emphasis on the massive stars in various configurations, and some concluding remarks are given in Section 3.

2 Production of Galactic cosmic-rays by massive stars

The role of massive stars in the production of Galactic cosmic-rays is well-established. The acceleration of charged particles can take place in various massive star environments, including bow shock runaways (BSRs), particle-accelerating colliding-wind binaries (PACWBs) and supernova remnants (SNRs). These categories of objects have a common property: they contain an outflowing plasma that produces hydrodynamic shocks, with pre-shock velocities of at least a few thousands km/s. This property is a necessary condition to drive a mechanism of particle acceleration (DSA). According to this mechanism, a small fraction of the charged particles present in the plasma will cross the shock and interact with magnetic turbulence on the other side of the shock. This interaction will scatter the charged particles, allowing a fraction of them to cross the shock backwards, and so on. It has been demonstrated first by Fermi (1949) that these 'reflections' of particles on either side of the shock increase the energy of the particles. Iteratively, each particle will gain a given amount of energy at each crossing of the shock front. Some particles leave the acceleration site after only a few crossings, but some others will stay 'trapped' for a much longer time-scale. As a result, the distribution of these particles as a function of the energy will be a power law, with a negative index (Fermi 1949, Longair 1992). The amount of energy gained by particles at each crossing is directly related to the pre-shock velocity: the relative energy gain $\Delta E/E$ is proportional to V/c (V being the pre-shock velocity and c being the speed of light). This process generates relativistic particle populations, and constitutes a good candidate for the production of cosmic rays in many astronomical environments. Given the quite high energy loss rate of relativistic electrons through various radiative processes (synchrotron radiation, inverse Compton scattering, or even relativistic bremsstrahlung) very close to their acceleration site, the cosmic-ray population penetrating molecular clouds is dominantly made of positively charged particles such as protons and helium nuclei.

The sources of cosmic-rays enumerated above (BSRs, SNRs and PACWBs) are located close to molecular clouds where their impact on astrochemical processes is expected to be the most significant. This proximity is explained by the rather short evolution time-scales of massive stars, with respect to other, less massive stellar objects. The evolution time-scale (up to about 10 Myr) is dictated by the nuclear burning rate, which is much higher for the most massive stars. For a comparison, the evolution time-scale of the Sun is about 10 Gyr. As a result, massive stars generally do not have the time to go very far from their formation site over their evolution time-scale. As they are formed from collapsing molecular clouds, most of them stay quite close to the densest parts of the interstellar medium. The interaction of cosmic-rays produced by massive stars in different configurations, or evolutionary stages, with the material of a molecular cloud is illustrated in Fig. 1.

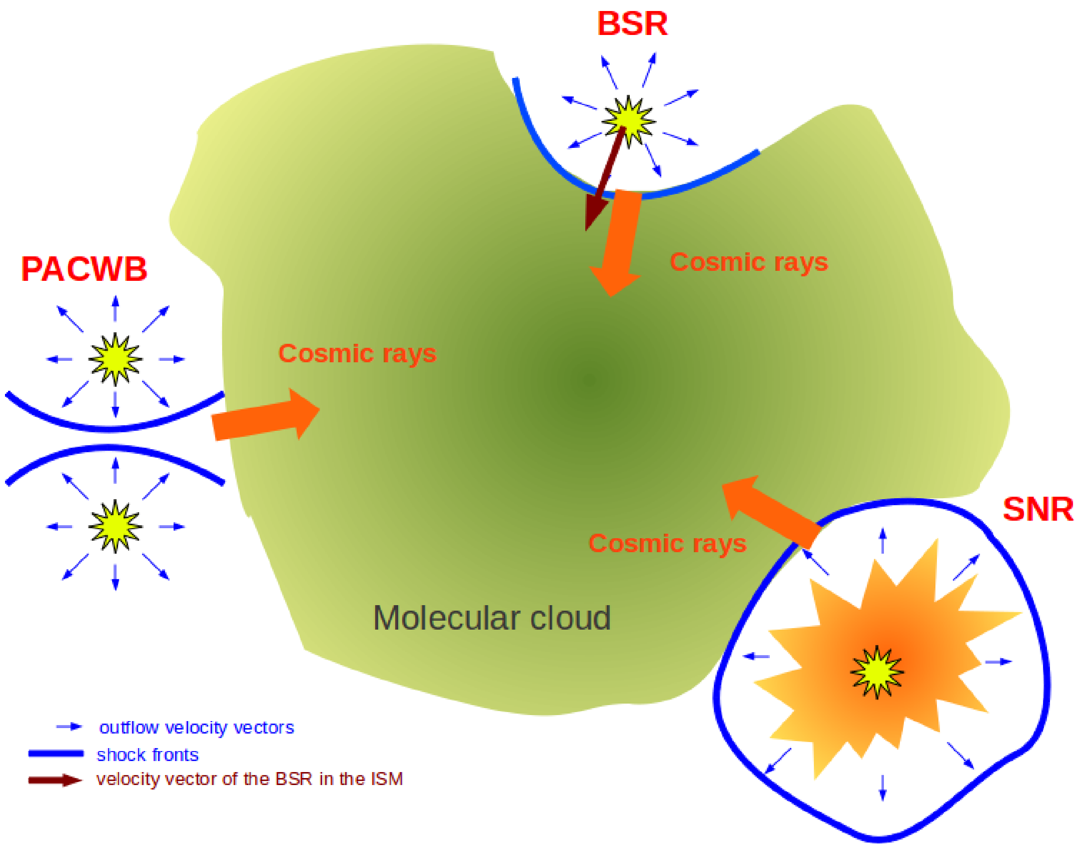

Figure 1: Schematic view of a molecular cloud, in the presence of sources of cosmic-rays such as a BSR, a PACWB and a SNR.

2.1 Bow shock runaways

On their evolution time-scale, massive stars do not generally have the time to leave their formation site. However, following supernova explosion in binary systems or dynamical interactions in dense stellar clusters, some of them may be kicked-off from their birth place (Blaauw 1961, Leonard &

Duncan 1990). Potentially, a few percent (up to 10%) of massive stars may be so called runaway stars, or simply runaways (Peri et al. 2012). Their high velocity, with respect to the surrounding interstellar medium, allows them to cross significant distances, and notably to go through clouds still rich in interstellar material. As a rule of thumb, a velocity of 1 km/s allows to travel a distance of 1 parsec over 1 million year. With typical velocities of several tens of km/s, runaways can therefore travel distances of the order of – or larger than – the typical length of molecular clouds. The interaction of their strong stellar winds with the interstellar medium will produce bow shocks. These shocks are generally revealed by infrared images, displaying typical bow-shaped emission regions whose apex is located in the direction of the velocity vector of the runaway. Such hydrodynamic shocks are able to accelerate particles (del Valle & Romero 2012, del Valle et al. 2015). Observational hints for the presence of relativistic particles have been found in the radio domain (Benaglia et al. 2010), in X-rays (López-Santiago et al. 2012), and potentially also in gamma-rays (del Valle et al. 2013). Their action as particle accelerators is expected to vary as a function of time, depending on the properties of the medium crossed by the runaway. The acceleration process may operate over several Myr, i.e. the evolution time scale of the massive star starting from its runaway status. Such systems constitute in situ sources of cosmic-rays when they cross molecular clouds where astrochemical processes are taking place.

2.2 Supernova remnants

Most massive stars end their evolution in a supernova explosion (Chevalier 1977, Georgy et al. 2009). The core shrinks to become a neutron star or a black hole, and the outer layers are violently expelled with speeds of several 1000 km/s (up to about 10000 km/s). This fast and abundant outflow of stellar material interacts with the interstellar medium, producing strong shocks able to accelerate particles up to energies of 10-100 TeV. The supernova is a quite brief event on astronomical scales, but the outflow can interact significantly with the interstellar material over several kyr (up to several tens of kyr): this is what is called a supernova remnant (e.g. Vink 2012). SNRs are known to be very efficient particle accelerators, certainly more efficient than PACWBs and BSRs. They certainly constitute the main source of Galactic cosmic-rays.

2.3 Particle-accelerating colliding-wind binaries

Most massive stars are found in binary (or higher multiplicity) systems, where stellar components orbit about their common center of mass (e.g. Sana et al. 2012,2014). In such systems, their strong stellar winds will collide with pre-shock velocities typically of a few 1000 km/s (see e.g. Stevens et al. 1992). These collisions will produce strong shocks allowing for the acceleration of particles up to relativistic energies though the DSA mechanism (see e.g. Eichler & Usov 1993, Pittard & Dougherty 2006, Reimer et al. 2006, De Becker 2007). These so-called relativistic particles include electrons, protons, alpha particles and even heavier ions. It is not clear yet whether all colliding-wind binaries are able to accelerate particles. However, the most recent inventory of these systems suggests that particle acceleration may be a rather frequent feature among massive binaries (De Becker & Raucq 2013), as these particle accelerators seem to cover a very large stellar and orbital parameter space.

An important point is that particle acceleration is likely to operate over the whole evolution time-scale, typically $\sim$ 10 Myr, i.e. as long as the two components are pre-supernova objects (not yet compact neutron stars or black holes) with strong interacting stellar winds. PACWBs are therefore able to accelerate particles over time-scales 100-1000 times longer than that of SNRs. As a result, the instantaneous population of PACWBs is certainly much more abundant than that of SNRs. This statement lends thus significant support to the idea that, despite their lower intrinsic acceleration efficiency with respect to supernova remnants, PACWBs are very likely to contribute to the production of Galactic cosmic-rays. The capability of these massive binaries to accelerate particles is restricted to energies below of a few GeVs for electrons, and potentially $\sim$ 1 TeV for protons. They are therefore clearly able to produce cosmic-rays at keV and MeV energies, known to be efficient at interacting with the content of molecular clouds (Padovani et al. 2014). As a result, even though particle-accelerating colliding-wind binaries are not key players for the investigation of very high energy cosmic-rays (e.g. significantly above the TeV regime), they are certainly significant contributors for the influence of cosmic-rays in astrochemical processes.

3 Concluding remarks

The main ideas conveyed by this short report can be summarized as follows:

- Massive stars at various evolutionary stages (before and after the supernova event), on in different configurations (in binary systems or as runaways) are known to be efficient providers of cosmic-rays in the interstellar medium.

- On their evolution time-scale, massive stars stay close to the regions of the Galaxy rich in interstellar material. These objects are therefore very close to molecular clouds where cosmic-rays will interact with atoms and molecules.

- These interactions will dissociate molecules, and ionize molecules and atoms. This will result in a significant activation of interstellar chemistry through ionic chemical pathways. These cosmic-rays will also interact with the material trapped in interstellar ices, as simulated in various experiments discussed in the framework of the present workshop.

- Massive stars can be viewed as the main providers of these high energy charged particles which play a crucial role in the interstellar physico-chemical processes at the origin of the diversity and complexity of molecules in space.

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References

Bell A.R., 1978, MNRAS, 182, 147
Benaglia P., Romero G.E., Martí J., Peri C.S. & Araudo A.T., A&A, 517, L10
Blaauw A., 1961, Bulletin of the Astronomical Institutes of the Netherlands, 15, 265
Chevalier R.A., 1977, ARA&A, 15, 175
Cravens T.E. & Dalgarno A., 1978, ApJ, 219, 750
Crowther P.A., 2007, ARA&A, 45, 177
De Becker M., 2007, A&ARev, 14, 171
De Becker M., 2013, BSRSL, 82, 33
De Becker M., 2014, Ap&SS, 350, 237
De Becker M. & Raucq F., 2013, A&A, 558, A28
del Valle M. & Romero G.E., 2012, A&A, 543, A56

del Valle M. , Romero G.E. & De Becker M., 2013, A&A, 550, A112
del Valle M. , Romero G.E. & Santos-Lima R. 2015, MNRAS, in press
Ehrenfreund P. & Charnley S.B., 2000, ARA&A, 38, 427
Eichler D. & Usov V., 1993, ApJ, 402, 271
Fermi E., 1949, Physical Review, 75, 1167
Georgy C., Meynet G., Walder R., Folini D., & Maeder, A., 2009, A&A, 502, 611
Herbst E., van Dishoeck E.F., 2009, ARA&A, 47, 427
Leonard P.J.T. & Duncan A.J., 1990, AJ, 99, 608
Longair M.S., 1992, High Energy Astrophysics, Cambridge University Press
López-Santiago J., Miceli M., del Valle M.V., Romero G.E., Bonito R., Albacete-Colombo J.F., Pereira V., de Castro E. & Damiani F., 2012, A&A, 757, L6
Muijres L.E., Vink J.S., de Koter A., Müller, P.E., & Langer, N., 2012, A&A, 537, A37
Padovani M., Hennebelle P. & Galli D., 2014, ASTRA Proceedings, 1, 23
Peri C., Benaglia P., Brookes D.P., Stevens I.R., & Isequilla N.L., 2012, A&A, 538, A108
Pittard J.M. & Dougherty S.M., 2006, MNRAS, 372, 801
Prasad S.S. & Tarafdar S.P., 1983, ApJ, 267, 603
Puls J, Vink J.S., & Najarro F., 2008, A&ARev, 16, 209
Sana H., de Mink S.E., de Koter A., Langer N., Evans C.J., Gieles M., Gosset E., Izzard R.G., Le Bouquin J.-B., & Schneider F.R.N, 2012, Science, 337, 444
Sana H., Le Bouquin J.-B., Lacour S., Berger J.-P., Duvert G., Gauchet L., Norris B., Olofsson J., Pickel D., Zins G., Absil O., de Koter A., Kratter K., Schnurr O., & Zinnecker H., 2014, ApJSS, in press
Stevens I.R., Blondin J.M., & Pollock A.M.T., 1992, ApJ, 386, 265
Tielens, A.G.G.M, 2005, The Physics and Chemistry of the Interstellar Medium, Cambridge University Press
Reimer A., Polh M. & Reimer O., 2006, ApJ, 644, 1118
Vink J., 2012, A&ARev, 20, 49
Yeghikyan A.G., 2011, ISRN Astron. Astrophys, doi:10.5402/2011/905015