Mem. S.A.It. Vol. 88, 608

Memorie della

Protostars as cosmic-ray factories

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Abstract. In recent years a wealth of observations of infrared/millimetre molecular lines in protostars led to estimate an unexpected high value of the cosmic-ray ionisation rate. Radio continuum observations in the same source types detected synchrotron emission that cannot be explained by standard models of cosmic-ray propagation in star-forming regions. We argue that jet shocks as well as shocks on protostellar surfaces can be efficient accelerators of local thermal particles through the first-order Fermi acceleration (or diffusive shock acceleration) mechanism. The presence of cosmic-ray sources within young protostellar objects can have unexpected repercussions on the ionisation degree of protostellar discs, on the process of star and planet formation, and on the chemistry of complex prebiotic molecules.

Key words. Cosmic rays – ISM: jets and outflows – Stars: protostars

1. Introduction

Cosmic rays are the main ionising agents of H_2, the most abundant component of molecular clouds. From this process, increasingly complex species are produced, up to the formation of prebiotic molecules. Cosmic rays also affect (*i*) the collapse time of a molecular cloud as well as the efficiency of star formation by influencing the collapse timescale through the gas-magnetic field coupling (Galli et al. 2006; Padovani et al. 2014), (*ii*) the thermal balance of a cloud, determining the gas temperature in particular density intervals (Galli & Padovani 2015), and (*iii*) the charge distribution on dust grains by cosmic-ray-induced UV photons (Cecchi-Pestellini & Aiello 1992; Ivlev et al. 2015). The presence of cosmic rays can be indirectly proved by different molecular tracers that allow to estimate the cosmic-ray ionisation rate, the key-brick parameter in chemical codes to interpret the abundance of the observed molecular lines (e.g., Indriolo & McCall 2012; Caselli et al. 1998). Its range spans from $\approx 10^{-15} - 10^{-16}$ s^{-1} in diffuse regions to $\lesssim 10^{-19}$ s^{-1} in protostellar discs. The decrease of the ionisation rate with increasing H_2 density has been explained as due to the attenuation of the cosmic-ray flux because of energy loss processes and magnetic focusing/mirroring (Padovani et al. 2009, 2011, 2013). Surprisingly, Herschel and IRAM-30m observations found very high values of the ionisation rate in two proto-Solar-like systems (4×

10^{-14} s^{-1} and 1.5×10^{-12} s^{-1} in OMC-2 FIR 4 Ceccarelli et al. 2014; 3×10^{-16} s^{-1} in the bow shock B1 of L1157 Podio et al. 2014) that cannot be explained as due to the interstellar cosmic-ray flux. In fact, most of cosmic rays have been braked while propagating in the protostellar envelope, losing their ionisation efficiency. For the same reason, the synchrotron emission observed in the bow shock of DG Tau (Ainsworth et al. 2014) cannot be explained by the interstellar flux of cosmic-ray electrons. In Padovani et al. (2015); Padovani et al. (2016); Padovani et al. (2017) we developed a model that explains these observations, showing that particle acceleration can be driven by shock waves occurring in protostars through the first-order Fermi acceleration mechanism so that protostellar shocks can efficiently accelerate local thermal particles, boosted up to mildly relativistic energies: in this sense protostars can be cosmic-ray factories.

2. Creation of cosmic rays in protostellar shocks

Several mechanisms with different levels of efficiency can explain the acceleration of particles in presence of shocks: turbulent second-order Fermi acceleration (Prantzos et al. 2011), acceleration by shocked background turbulence (Giacalone & Jokipii 2007), acceleration in magnetic reconnection sites (de Gouveia Dal Pino & Lazarian 2005) as well as shear acceleration at the jet-outflow interface (Rieger & Duffy 2006). We focus on the first-order Fermi acceleration, also known as diffusive shock acceleration mechanism, as proposed in Padovani et al. (2015); Padovani et al. (2016); Padovani et al. (2017). Charged particles gain energy when passing through a shock, but an efficient acceleration only occurs in presence of magnetic fluctuations around the shock. These fluctuations cause the pitch angle scattering so that particles can cross back and forth the shock many times, reaching relativistic energies, until they escape in the downstream medium (see, e.g., Drury 1983).

A set of conditions must be satisfied in order to have an efficient acceleration: charged particles have to be accelerated before they start to lose energy because of collisions with neutrals and before escaping by diffusion processes (e.g., in the transverse direction of a jet). The acceleration timescale has also to be shorter than the dynamical timescale of the shock (e.g., $\approx 10^3$ yr for a jet shock or $\approx 10^5$ yr for a protostellar surface shock; de Gouveia Dal Pino 1995 and Masunaga & Inutsuka 2000, respectively). Finally, in protostars the medium is not fully ionised so that the friction between neutrals and ions can powerfully quench the acceleration. This adds a further requirement: neutrals and ions have to be coupled, namely they have to move coherently, so that ion-generated waves are weakly damped and acceleration can take place. Ion-neutral coupling occurs when the momentum transfer rate from ions to neutrals is larger than the wave pulsation (Drury et al. 1994).

The above conditions rely on a number of parameters related to the shock (magnetic field strength, total hydrogen density, flow velocity, shock radius, ionisation fraction, temperature, upstream diffusion coefficient, and shock efficiency) and they constrain the maximum energy attained by a thermal particle traversing the shock. In Padovani et al. (2015); Padovani et al. (2016) we show that protons can be efficiently accelerated both in jet shocks and in shocks on protostellar surfaces, but not in shocks of Class 0 collapsing envelopes. Even if the maximum energy reached is only of the order of $10-30$ GeV, it is enough to locally increase the ionisation rate by orders of magnitude, allowing to explain the high values of the ionisation rate estimated by observations in some low-mass Class 0/1 protostars (Podio et al. 2014; Ceccarelli et al. 2014).

Acceleration of thermal electrons is less efficient and the energy of the secondary generation of electrons produced by the ionisation of hydrogen atoms/molecules due to locally accelerated protons is also too low to explain the observed synchrotron emission. However, a common feature in protostars is the presence of a number of shocks all along their jets. Melrose & Pope (1993) showed that previously accelerated particles are reaccelerated when crossing consecutive shocks. In Padovani et al. (2016) we show that this reacceleration mechanism also involves secondary electrons that are boosted up to relativistic energies, providing an explanation for the synchrotron emission seen towards the bow shock of DG Tau (Ainsworth et al. 2014).

3. Conclusions and prospects

We examined the possibility of generating cosmic rays within a protostellar source by means of shock processes and we found that jet shocks as well as shocks on protostellar surfaces can efficiently accelerate local thermal particles. Finding evidence of a local source of energetic particles within solar-type protostellar objects may have important consequences: (*i*) local cosmic rays could be responsible for the formation (by spallation reactions) of short-lived radionuclei contained in the calcium-aluminium-rich inclusions of carbonaceous meteorites, such as ^{10}Be; this finding would support the theory that meteoric ^{10}Be was formed in situ by spallation reactions, rather than moved from the solar atmosphere (Ceccarelli et al. 2014; Padovani et al. 2016); (*ii*) a local cosmic-ray source would also help in explaining the formation and the presence in the gas phase of complex organic molecules (COMs). In fact, cosmic rays induce stochastic heating on dust grains, allowing surface radicals to move faster at lower temperature then increasing the abundance of COMs; the same cosmic rays would also be responsible for desorbing COMs from dust grains (Reboussin et al. 2014); (*iii*) cosmic rays created inside protostars could also propagate towards the disc, causing an increase of the ionisation fraction and keeping the magneto-rotational instability active, with consequences on the mass and angular momentum transport in the star-disc system (Gammie 1996).

So far we applied our model to low-mass protostars, but we expect the cosmic-ray acceleration to be even more powerful in high-mass sources, where shock velocities are larger also far from the central source. In this case protons may reach energies of the order of 1 – 10 TeV and their γ emission could be detected by telescopes such as H.E.S.S. or CTA. The synergy between infrared/millimetre molecular line and radio/gamma-ray continuum observations will help in understanding whether and to what extent the process of local cosmic-ray acceleration is common during the different phases of star formation.

Acknowledgements. MP acknowledges funding from the European Unions Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 664931.

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