Editorial: Plasma, particles, and photons: ISM physics revisited

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1 Summary

Interstellar medium (ISM) research has made significant progress in recent years thanks to advances in observational techniques, an increase in computing power to run simulations, and the development of new methods of analysis. We expect even more exciting results from new missions and future observatories like the Square Kilometre Array, James Webb Space Telescope, Athena X-ray Observatory, the Cherenkov Telescope Array, or the KM3NeT experiment.

In this topical collection we collect reviews and new results in ISM research with an emphasis on multi-messenger Astrophysics. There are contributions on the production of cosmic ray (CR) electrons (Alsaberi et al. 2019) and their transport (Heesen 2021) as deduced from observations, the generation of X-rays and cosmic γ-rays in interstellar shocks (Sano and Fukui 2021), the mechanism of particle acceleration via diffuse shock acceleration (Urošević et al. 2019), the thermal and non-thermal X-ray emission from superbubbles (Kavanagh 2020), and the characteristics of non-equilibrium ionisation plasmas (Breitschwerdt and de Avillez 2021). Next, there are contributions on simulations of cosmic ray propagation (Mertsch 2020), on their detection (Albrecht et al. 2022) and what we can learn from that, on interstellar radioactive isotopes (Diehl 2021), and on observations of neutrinos (Kheirandish 2020).

We hope this serves as an overview of recent progress in the study of the ISM along with new approaches for an improved understanding of the interstellar medium in galaxies and the ISM’s role in galaxy evolution.

2 The multi-phase interstellar medium

As we know from observations from the radio via the infrared to the optical, the vast space between the stars and stellar remnants in the Milky Way is filled with cool gas and clouds \((T \lesssim 10^2 \text{ K})\) with densities of \(n > 10 \text{ cm}^{-3}\), embedded in a warm \((T \approx 10^4 \text{ K}, n \approx 0.1 \text{ cm}^{-3})\) intercloud medium of partially ionised hydrogen (Cox 2005, and references therein). In addition, a phase with a much higher temperature had been suggested for the interstellar gas (Spitzer 1956) even before the 1970s, which is when observations in the ultraviolet and the X-rays revealed the presence of hot gas at coronal temperatures \((T \approx 10^6 \text{ K})\) in the interstellar medium (ISM).

Further observations revealed absorption features in optical spectra of bright stars at high Galactic latitudes which are indicative of clouds at relatively large distance from the Galactic plane, providing evidence for the presence of hot tenuous gas also beyond the Galactic plane, in the halo, in which these clouds are embedded.

Galaxies evolve because stars do. During its short lifespan a massive star sheds matter in the form of stellar winds and ends its life in a core-collapse supernova. As for a low-mass star, a white dwarf formed at the end of its lifetime can be in a close binary systems with a star or another white dwarf, and accretion of matter from the companion onto the white dwarf can again lead to a supernova. In a supernova explosion, stellar material is expelled into the environment at high velocities of a few % of the speed of light. Moreover, nucleosynthesis occurs under the extreme conditions of the explosion, forging new elements and isotopes, which are then also freed to the interstellar medium (Diehl 2021).
The stellar winds of massive stars as well as the final explosion cause strong shock waves that expand into the ambient medium and create an interstellar bubble or a supernova remnant (SNR). In the shock waves, the stellar ejecta and the ambient medium is heated to high temperatures of $10^6$–$10^7$ K forming a low-density plasma. For interstellar shock waves to arise, ionisation in the medium is required, and the acceleration of particles in the shocks and the amplification of magnetic fields in the interstellar plasma are strongly coupled (Breitschwerdt and de Avillez 2021). In the strong shock waves of stellar winds and supernovae, particles are accelerated to very high energies (Urošević et al. 2019) which then diffuse through interstellar space and are observed on Earth as cosmic rays. The shock waves will also encounter inhomogeneities in the interstellar medium. In particular, the interaction of the shock with cold and dense interstellar clouds is believed to lead to significant amplification of the interstellar magnetic fields and hence to strong emission from non-thermal particles (Sano and Fukui 2021). The emission of the thermal shocked plasma is detected in X-ray observations, while emission from non-thermal relativistic particles can be observed over the entire electromagnetic spectrum from radio (e.g., Alsaberi et al. 2019) all the way up to TeV energies.

As stars in galaxies are usually born not as single objects but in associations or clusters, stellar wind bubbles around massive stars and supernova explosions often occur in the same place inside a galaxy and more or less at the same time. Strong stellar winds and supernovae form a cavity filled with hot plasma and sweep up colder gas around it, giving rise to new structures in the ISM. SNRs may also produce an interconnecting system in the ISM filled with hot gas as suggested by Cox and Smith (1974). Since the cooling of the hot low-density gas is very inefficient once heated, the hot interstellar plasma will persist for millions of years or longer (e.g., Sutherland and Dopita 1993; Breitschwerdt and de Avillez 2021) and form large interstellar structures with sizes of typically 100–1000 pc called superbubbles (Kavanagh 2020). The shells of cold gas around superbubbles eventually fragment and become new sites of star formation. Although gravitation is considered to be the driving mechanism for the formation of stars out of the densest cores in molecular clouds (see review by Zinnecker and Yorke 2007), observations have shown that gravitation alone is often not sufficient, but additional compression by shocks like in SNRs or interaction of high-energy particles with the cold ISM seem to be necessary to trigger star formation (Elmegreen 1993; Padovani et al. 2020, and references therein). Therefore, a combined study of radiation, shocks, plasma, and relativistic particles in the ISM is crucial for the understanding of the matter cycle in galaxies.

To understand the observables of the non-thermal part of the interstellar medium, the following theoretical aspects need to be understood:

1. **Cosmic-ray acceleration:** Observations of cosmic rays and their secondaries show that it is necessary to accelerate particles up to at least $10^{15}$ eV in the Milky Way (see e.g., Urošević et al. 2019, for a review). This is a true challenge, as (i) to get particles out of their equilibrium distribution into a process that allows for their efficient acceleration via processes like diffusive shock acceleration is a problem of its own; (ii) in addition, even when ignoring the injection problem by injecting the particles as a pre-accelerated population, reaching maximum energies of $10^{15}$ eV is extremely difficult. Supernova remnants are believed to be the primary source in the Milky Way on the basis that they can provide the observed energy budget.

2. **Cosmic-ray transport** changes the observed energy spectrum, level of isotropy, and composition at a given energy. Transport can be dominated by a diffusive behaviour, but it can also be of a quasi-ballistic or advective nature (Mertsch 2020). These different scenarios can for once be distinguished by the different energy dependencies that enter the final cosmic ray spectrum. Moreover, the shape of the outflows observed in edge-on galaxies can discriminate between different transport mechanisms such as diffusion or advection (Heesen 2021). However, as the observed spectra are entangling acceleration, transport, and loss processes, the interpretation remains difficult and is in need of a large set of observables while taking into account the level of (an)isotropy of cosmic rays, the magnetic field structure, gas distribution, as well as the medium’s composition (electrons, protons, heavier nuclei).

3. **Radiation and interaction processes:** In understanding the physics of (1) and (2), direct observations of cosmic-ray hadrons (protons to iron nuclei) can be interpreted in a theoretical framework. The understanding of cosmic-ray electrons, however, is in need of a full understanding of loss processes such as synchrotron and inverse Compton radiation, and Bremsstrahlung. These processes not only result in the emission of a broadband photon field from radio to TeV energies, they also affect the electron spectrum as measured directly at Earth, via a loss term in the transport equation. Furthermore, in the interpretation of high-energy gamma-ray data, hadronic interactions like proton-proton, and proton-$\gamma$, play a decisive role. In these inelastic scattering processes, $\gamma$-rays and neutrinos are being co-produced via the production of multiple pions, illustrated with an example of proton-proton interactions:

$$pp \rightarrow \#(\pi^0, \pi^\pm)$$

with the charged pions decaying to

$$\pi^- \rightarrow \mu^- \bar{\nu}_\mu \rightarrow e^- \bar{\nu}_e v_\mu (\bar{\nu}_\mu)$$

$$\pi^+ \rightarrow \mu^+ v_\mu \rightarrow e^+ v_e \bar{\nu}_\mu (v_\mu)$$

(1) (2) (3)
Here, the multiplicity of the produced number of neutral and charged pions is a function of the energy (Albrecht et al. 2022). In fact, the observation of the particles in the Earth atmosphere, which arise from the interactions of cosmic-ray hadrons (mostly protons) with molecules in the atmosphere helps us understand these multiplicities and cross sections, especially when combined with data from particle accelerators, see Albrecht et al. (2022). Such knowledge is vital when interpreting gamma-ray emission from astrophysical sources, as the spectral behaviour produced for a hadronic interaction allows us to distinguish it from the leptonic one arising from inverse Compton scattering or Bremsstrahlung of relativistic electrons. It is equally important in the prediction of high-energy neutrino fluxes (Kheirandish 2020). From IceCube measurements in combination with different theoretical arguments, we know that the observed high-energy neutrinos from the cosmos do not originate in the Milky Way alone, and that extragalactic sources like Seyfert-starburst composites, or radio-loud active galaxies are the most promising candidates.

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