Feedback from young stars, the molecular signature of shocks and outflows

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Abstract. Why do we study shocks ? Because they are there. Shocks are ubiquitous in the interstellar medium (ISM), where they constitute a major source of energy injection, together with photons and cosmic rays (CRs). Galactic shocks, and converging flows at the basis of the formation of molecular clouds and filaments, are examples of interstellar shocks. Shock waves are also generated during the birth, life and death of stars in the form of jets and protostellar outflows, stellar winds and supernovae and supernova remnants (SNRs). Hence, they are a major route of feedback of stars on galaxies. As such, they are a proficient tool to better understand the cycle of matter and energy in galaxies, but also the formation of stars. In this review, I will describe the recent advances on the study of shocks that can be observed and characterized with the IRAM instruments, with emphasis on the study of protostellar jets and outflows.

1 Introduction

In this review, I first focus on the direct questions in relation with shock phenomenology: what are the processes at work and how we progressively overcame our limitations on their understanding (section 2). I will then show how we measure energetic and chemical impacts of interstellar shocks (section 3). And finally, beyond the phenomenology of shocks, I will describe the general properties of protostellar jets and outflows and subsequent star formation that we can infer from their observations (section 4).

2 Mechanisms at work

Physical description. Interstellar shock waves are best described by numerical codes that self-consistently calculate the thermodynamical, physical, dynamical and chemical state of a one-dimensional layer of gas in stationary conditions. A reference for such code is the Paris-Durham model, that also allows to approximate the propagation of a non stationary shock wave ([1] and references therein). Depending on the pre-shock parameters (density, ionization, magnetic field...) and shock characteristics (velocity), it allows to simulate the propagation of various kinds of shocks. Combined with a radiative transfer it has been used to intperpret observations in a number of protostellar outflows and SNRs (e.g., [2], [3], [4], [5], [6]). In some cases, more simple, parametric approaches have been used (e.g., [7], [8]).

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Limitations: geometry. An important limitation of such otherwise sophisticated models is the way they treat the geometry of the shock structure. Getting observationally close to resolving a one-dimensional shock structure has been claimed in [9] but remains challenging. Using the spectral resolution of observational infrastructures such as SOFIA has been proposed by [10] and [11] but this raises the question of modelling line profiles, that necessitates at least an approximate 3D modelling. So-called pseudo 2D or 3D solutions have recently been implemented, where collections of 1D structures are 'stitched' onto a 2D or 3D structure to model the optically thin emission of H_2 maps ([12], [13]), or line profiles and excitation diagrams ([14]).

Limitations: irradiation. Another limitation until very recently came from the lack of models enabling to simultaneously treat the effects of shocks and energetic UV photons. This effect was exposed when e.g. [15] or [16] tried to interpret fine-structure emission lines observed with *Herschel* by the same shock models that were so successful in accounting for H_2, CO or SiO emission. The energetic photons, in these cases come either from an external source of radiation (like a massive protostar in a protostellar outflow), or from the shock itself (for high velocity shocks, above 30 km s^{-1}). Both requirements have been addressed more or less recently: by [17] for the former, and [18], [19] and [20] for the latter.

The next steps. The (ongoing) next steps in terms of modelling consist in developing pseudo-3D solutions for optically thick lines, and providing user-friendly and standard, extensive grid of models covering as many input parameters as necessary. Observationnally, these new tools will allow to interpret observations of shocks closer to the protostar ([21], [22], [23], [24], [25],...) including accretion shocks (where the material falls on the disk - [26], [27], [28],...). They will also provide support to interpret observations from high-mass protostellar regions ([29], [30], [31], [32],...), and also from later feedback stages ([33], [34], [35],...). These new shock models are fed with more input parameters, and require more observational constraints. Multi-wavelengths studies will be needed. Instruments such as the IRAM30m, NOEMA, Yebes40m, APEX or ALMA ones, sometimes aimed at new lines (like recombination lines, e.g. [36] with APEX, [37] with the IRAM30m, and [38] with the Yebes40m), will have to be combined with JWST, Spitzer or ISO (to observe H_2, but also OH and H_2O), IRTF (to observe CH^+, [39]), and SOFIA, or *Herschel* ([40], [41], [42], [43], [44], [45]...). Fine-structure, but also meta-stable lines in the optical and UV ranges, as well as Lyman α and β lines will also bring new constraints (observed with the VLT for instance, see [46], [47], [48]...).

3 Impact of shocks

Energetic impacts: isolated outflows. Measurements of the energetic impacts of protostellar shocks have been performed since the observation capabilities have reached the necessary spatial and spectral resolutions [49]. Interpreting observations by means of shock models is a sophisticated way to measure the energetic impacts of shocks at one position [5]. Since it requires both numerous observations and an easy access to grids of shock models, this method has only been performed over shock positions, and not generalized. In fact, observational studies can provide a more direct access to e.g., the momentum, the mechanical force, the kinetic energy, and the associated luminosity of a shock, not only on one position, but over entire maps, i.e., potentially over several spatial scales (see e.g. [6], where an analysis of CO lines observed by NOEMA, the IRAM-30m, and other telescopes led to the classification of Cep E as a jet-driven outflow, see also [50]).

Energetic impacts: perspectives. IRAM instruments have a key role to play in the evaluation of energetic impacts of shocks in more and more interstellar regions. With multiple beam receivers combined with wide-band receivers, the required observations of various lines of various isotopologues of CO will be much faster than it is now, enabling us to map large portions of the interstellar medium. This perspective is particularly interesting to map entire filaments possibly originating from cloud-cloud collisions, or evolved SNRs interacting with the ISM over tens of pc (see e.g. the CO observations presented in [51], and the energetic parameters in [52]). Interferometers will also open new perspectives in this direction: if short-spacings observations are performed and allow to recover the flux missing from these generally bright lines, then a next step could be to quantify the energetic impact of clusters of protostellar outflows, whether these are low-mass (like NGC1333, e.g. [53, 54]) or high-mass (like W43-MM1, see [55, 56]).

Chemical impacts: SiO. SiO has been considered the ultimate shock tracer for a long time. The classical intepretation for its systematic association to shock regions was that it is necessary to have a rather violent (velocity above 25 km s^{-1}) shocks to release the silicon almost entirely locked in grain cores in the quiescent medium. This necessary sputtering was made possible by the existence of a drift velocity between neutrals and charged grains, a requirement met in C-type shocks (see [57], [58], [59], with reference observational papers such as [60]). On the other hand, the interpretation of the SiO emission from young shock regions (nearby the protostar in jets and outflows, [61], [2], [6]), or the inclusion of grain-grain interactions in shock models ([62], [63], [64]), and more recently the interpretation of extended SiO emission in low-velocity shock regions (e.g. [65], [66], [67], [68], [69],...) made it necessary to adopt another model where a small fraction (1 to 10%. of the elemental solar neighborhood value) of silicon is free in the pre-shock phase (in a form depending on the conditions in the pre-shock region). In such conditions, SiO formation can be achieved above 3 km s^{-1} (chemical route) or $\sim$12 km s^{-1} (mantle sputtering route; [55]). One must then explain one SiO is not detected/observed elsewhere: in the diffuse medium, it could be due to photodissociation and ionization into Si and Si^+. In the dense medium, it could be due to freeze-out on grains or to conversion into SiO_2.

Chemical impacts: systematic studies. Beyond SiO, the IRAM instruments have played a pivotal role in the study of chemical impacts of shocks so far, and should continue to do so. Among the large programs that have brought several breakthroughs, one can cite SOLIS (Seeds Of Life in Space) with NOEMA ([70]), ASAI (Astrochemical Surveys At IRAM) with the IRAM-30m telescope ([71]), and CALYPSO (Continuum And Lines in Young Protostellar Objects) with both telescopes ([72], [73]). A source like L1157-B1, for instance, has been extensively observed to study the chemistry of silicon (SiS, [74], and SiO, [75]), sulphur (H_2S, [76]; CCS, H_2CS, OCS, SO, SO_2, [77], [78]), but also nitrogen (formamide, [79], NO, [80], DCN and $H^{13}CN$, [81], HCN/HNC, [82], HC_3N and HC_5N, [83], $H^{13}CN$ and $HC^{15}N$, [84]), and phosphorus (PO and PN, [85]). The production of complex organic molecules in this region was also studied by [86], [87], and [73], each time involving IRAM instruments. Interestingly, recent observations of the Cep E protostellar outflow by [88] might serve as a basis for irradiated shock studies.

4 Jets and outflows

General properties. Protostellar jets and outflows can also be studied for themselves rather than for shock-related goals. In this case, observations by IRAM or IRAM-like telescopes usually shed light on the process of star formation. The recent CALYPSO program was the first survey dedicated to globally characterize properties (presence of wide angle winds and high-velocity jets, jet mass loss rates, total jet power...) of outflows from young Sun-like stars with NOEMA ([89], with an equivalent ALMA program, see [90]).

Episodicity. The recent advents of interferometry also enabled to measure the episodicity of jets and outflows driven by low-mass ([91]), intermediate-mass ([92]), and high-mass protostars embedded in a protostellar cluster (W43-MM1, see [56]), with an episodicity in the ejection process occurring at dynamical timescales of tens to hundreds years, confirming the episodic nature of star formation processes.

Precession. The precession of jets and outflows was also more and more studied, specially around low-mass protostars (e.g., L1157, [93], SVS 13, [94], and IRAS 15398, [95]). Recently the precession of the intermediate-mass Cep E system was studied by [92]. The authors usually use models by [50] or [96] to describe the precession caused by either the orbital model of a binary system (when the precession has a W shape), or by the precession of the inner disk induced by a companion on inclined orbit (see also [97]). In the case of Cep E, the role of the B protostellar companion reported in [98] was excluded, but the authors were able to place constraints on a tighter possible companion (located at 10 to 40 AU from the protostar driving the Cep E outflow).

Launching mechanisms. At very high angular resolution, the recourse of interferometry has enabled to test theories of launching mechanisms for jets and outflows. The theoretical, magneto-hydrodynamical (MHD) disk wind model first developed by [99] was progressively moved closer to the observations by [100, 101]. It has now been tested in the HH212 system by [21, 22, 25, 102, 103]. Although very high angular resolution is required, these studies offer interesting perspectives for our understanding of a key process occurring almost systematically during the formation of stars.

5 Perspectives

Observations and models have progressed in parallel these past years, and more interaction is probably needed between these too distinct communities. Confrontations must systematized between observations and models. From this respect, observations must be as multi-wavelengths as possible, and include constraints on magnetic field properties. Models need to include radiative transfer, and also pseudo 3D effects. In this necessary dialog, the IRAM telescopes will play an instrumental role in the coming years, towards a more complete understanding of the formation of stars and better measurements of their feedback on the ISM.

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