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The role of colliding galaxies and tidal dwarf galaxies in the ISM/IGM enrichment

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Abstract. This review discusses the processes associated with galaxy collisions that contribute to the enrichment of the interstellar and intergalactic medium. Chemical evolution is driven by two main effects: (a) local enrichment of the ISM/IGM following star formation episodes triggered by collisions, occurring in two main modes, (1) a nuclear starburst, which results in superwinds/outflows, with injection of metals up to the intergalactic medium, (2) extended star formation episodes locally enriching up to large distances the surrounding ISM, and even the IGM when occurring within extended tidal tails and in tidal dwarf galaxies (b) radial mixing of the gas, with (1) the funneling of metal–poor gas in the central regions and a dilution of the metals there, (2) the transport of pre-enriched dusty gas towards external regions including tidal structures. The net effect is a flattening of the metallicity gradient of colliding galaxies, which is predicted by numerical simulations and observed in real systems. The last part of the paper addresses and belittles the specific contribution of collisional debris, especially tidal dwarf galaxies, in the pollution of the Universe.

Key words. Galaxy: abundances – Cosmology: observations

1. Introduction

The role of galaxy collisions on the evolution of galaxies has been a matter of debate, and fashion, for about 40 years. Collisions are at the heart of the hierarchical cosmological model – in fact mergers between dark matter halos rather than their baryonic counterparts, i.e. galaxies –. They are believed to be responsible for the morphological transformation of galaxies, and in particular the building up of massive ellipticals through major or minor mergers. They trigger intense starbursts, e.g. those observed in ultraluminous infrared galaxies (ULIRGs) in the Local Universe and in the submm galaxies at higher distances. The role of collisions in the production of (super) star clusters and even globular clusters has been addressed in a number of observational and simulation papers.

In comparison, the chemical evolution of the interstellar medium (ISM) and enrichment at large scale of the intergalactic medium (IGM) following galaxy collisions has been less studied. This topic to which this contribution is devoted is closely connected to studies of the star formation history (SFH) of galaxies, outflows and feedback processes. A specific emphasis is also made on collisional tidal debris. Indeed, collisions and associated tidal forces inject pre-enriched material in the intergalactic medium, a process that may be as efficient as stellar outflows, though much less discussed. Furthermore, tidal dwarf galaxies which may form within these debris have been claimed to play a potential significant role in polluting the IGM. Indeed, they host vigorous starbursts, but being dark matter poor, may not be able to keep their metals.

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2. ISM/IGM enrichment via collisions

Fig. 1 presents the nearby interacting system M81/M82/NGC 3077, which illustrates the variety of phenomena associated to collisions that impact the ISM/IGM enrichment, from triggered star formation and superwinds to gravitational effects. The M81 system will serve as a guideline all along this paper.

2.1. Merger induced star formation

The discovery and census with the IRAS satellite of luminous infrared galaxies has highlighted the apparent close connection between starbursts and galaxy collisions: indeed all ULIRGs in the local Universe are advanced mergers (Sanders & Mirabel 1996). Since then, numerous studies, relying on observations and simulations, have tried to quantify the effect and addressed questions such as: do all interactions trigger star formation? How does the star formation rate (SFR) evolve during the merger sequence? Reversely, are all strongly star-forming galaxies, or starbursts, associated to interaction events?

2.1.1. Triggered starbursts

As seen on Fig. 1, the distance between M81 and M82 is still about 50 kpc; yet star formation in both galaxies has already been enhanced following the interaction: the triggering of star formation occurs well before the merger. The evolution of the star formation rate as a function of the projected distance between the interacting galaxies, a proxy of the time sequence, has been quantified by Ellison et al. (2013), based on statistics of galaxy pairs in the SDSS. A (slight) increase of the SFR already occurs at projected distances of 50 kpc. Globally, their average SFR enhancement is $\times$ 3.5. The scatter is large and many additional parameters, such as the initial gas content, orbital parameters, etc., influence the star-formation history, as shown by numerical simulations.

The star formation history of mergers has been reproduced, among others, by Di Matteo et al. (2007), using large sets of mergers in which the dark matter, stellar and gaseous components are simulated. The effect of prograde vs retrograde encounter and impact on the fueling of gas inside the central regions (where a nuclear starburst is triggered) has been particularly studied. However, most of such simulations failed at producing starbursts with the intensity observed in local ULIRGs, i.e. an enhancement of at least a factor of 10 with respect to pre-encounter conditions. Recently, Teyssier et al. (2010) and Bournaud et al. (2014, in prep.) realized that the shape of the SFH and level of SFR enhancement largely depends on the spatial resolution of the simulation. A parsec scale resolution seems required to reach SFR peaks above 100 $M_{\odot}$/yr. This is likely due to the fact that two processes triggering SF are observed in mergers: the infall of gas into the central regions, reproduced by the old simulations, plus a global increase of the gas turbulence, inducing the conversion of low density gas into dense one and thus triggering large-scale, extended, star formation episodes. High resolution is needed to properly take into account this second process.

2.1.2. Outflows due to superwinds

A cone of ionized, UV and infrared emitting gas, centered on the nucleus of M82, is visible on Fig. 1. It is caused by superwinds associated with a nuclear starburst. The combined winds from massive stars have veloci-

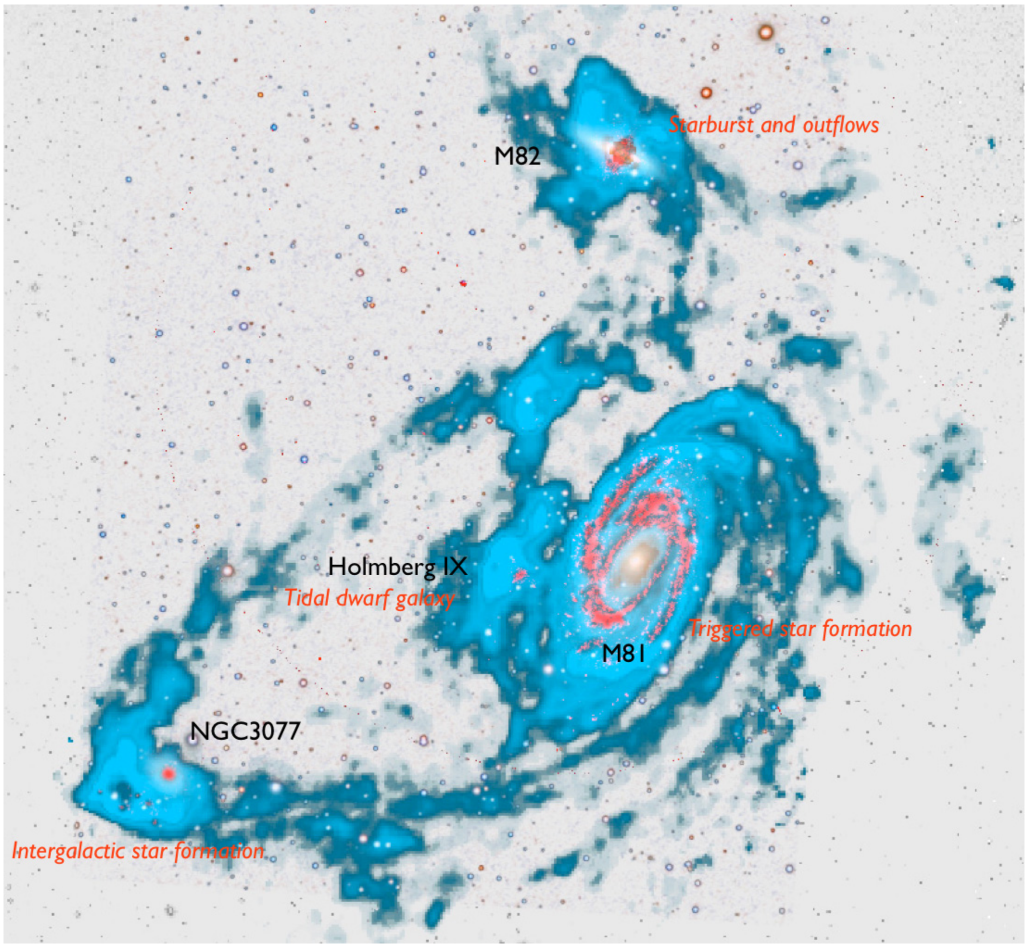

Fig. 1. The nearby colliding system M81/M82/NGC 3077. A VLA HI map (Yun et al. 1994) is superimposed in blue on an optical true color image. The far UV emission from GALEX is shown in red. The figure illustrates the variety of phenomena associated to collisions that may impact the ISM/IGM enrichment, namely: the pulling out of pre-enriched gas material from galaxies and injection into the intergalactic medium; the flattening of the metallicity gradient of the spiral galaxy M81, likely due to the gravitational interaction (Patterson et al. 2012); triggered star formation in the disk of M81 following the increased gas turbulence due to the on-going collision; nuclear starburst in M82 and associated stellar outflows, directly injecting dust and metals into the IGM (Lehnert et al. 1999); intergalactic star formation south of NGC 3077, i.e. in situ SF in gaseous collisional debris, made of HI and molecular gas (Walter et al. 2006); the formation of a tidal dwarf galaxy, Holmberg IX (Sabbi et al. 2008).

ties reaching or superseding the escape velocity of the galaxy. They therefore will not only enrich the local ISM but also inject heavy elements and dust into the IGM. Superwinds are usually believed to be the primary responsible for the enrichment of the IGM, including the intracluster medium (ICM) which has an average metallicity of about 1/3 solar. When not directly imaged, the winds are observed through a broadening of characteristics emission lines tracing the ionized or molecular component. Stellar winds contribute to the feedback mechanism, a key parameter of numerical simulations and galaxy evolution models, but the importance of which is still not well constrained by observations.

2.2. Gas mixing

Fig. 1 reveals that a large fraction of the atomic hydrogen in the M81 group is located along tidal structures, i.e; outside the disk of the three main group galaxies. Whereas only a few percent of stars is pulled out from galaxies in major mergers, between 10 and 50 percent of the gas may end up in the intergalactic medium; as mentioned earlier, another fraction of it loses its angular momentum and is driven towards the central regions, fueling a nuclear starburst (see review by Duc & Renaud 2013). The radial mixing of the gas will affect the metallicity profile of the interacting galaxies and contribute to the enrichment of the intergalactic medium. Indeed, the gas injected in the IGM by tidal forces is metal–rich, dusty and is at least partly made of molecular gas. *For instance CO has been detected at the tip of the southern tidal arm of M81 (Walter et al. 2006).*

2.3. Chemical evolution of colliding galaxies

Stellar feedback and the radial mixing of the gas drive the chemical evolution of colliding galaxies. The central regions experience the competing effects of the metal enrichment of the ISM due to the nuclear starburst and dilution following the inflow of metal–poor gas. Simulations have measured their relative strength as a function of time (e.g. Montuori et al. 2010; Torrey et al. 2012). In the external regions, local enrichment due to the extended mode of star formation, plus the tidal stretching of the gas distribution, will both contribute to increase the local metallicity. As a result, colliding galaxies should exhibit a metallicity profile which is flatter than isolated galaxies. This flattening and even possibly an inverse gradient has been observed in distant (Queyrel et al. 2012) and nearby (Kewley et al. 2010) colliding galaxies, *including in the M81 spiral galaxy (Patterson et al. 2012)*. Oxygen abundances in collisional debris (e.g. Weilbacher et al. 2003) close to solar values have been measured up to distances exceeding 50 kpc.

3. Focus on collisional debris and tidal dwarf galaxies

The huge reservoir of intergalactic metal enriched gas, including molecular gas, present in the environment of colliding galaxies fuel in-situ star-formation. *As shown on Fig. 1, ongoing intergalactic star formation is observed in the M81 group at relatively high levels South of NGC 3077 and East of M81, and at very small levels all along the tidal features (de Mello et al. 2008).* In fact, in other interacting systems, intergalactic star forming regions appear as scattered compact H II regions, series of equally spaced knots – the so called beads on a string –, or in relatively rare cases as condensations as massive as galaxies. They are qualified as tidal dwarf galaxies (TDGs) when they are gravitational bound objects.

3.1. Stellar populations in tidal dwarf galaxies

The dwarf galaxy Holmberg IX is likely a TDG formed during the collision between M81 and M82. This is likely the closest tidal dwarf identified so far and the only one which could be resolved with the HST in stars (Sabbi et al. 2008). Color magnitude diagrams indicate it is composed of stars with an age exceeding 1 Gyr, likely tidally expelled from its parent galaxy, and younger ones formed less than 200 Myr, which contribute to at least 20% of the total stellar mass. As shown by the modeling of their spectral energy distribution (Boquien et al. 2010), a large contribution of coeval young stars is a characteristic property of TDGs. Simulations predict it could be up to 100 % (Duc et al. 2004) for the most massive TDGs which are originally almost purely gaseous.

3.2. TDGs and ISM enrichment

Another structural property of TDGs is their lack of dark matter. In principle, this make them fragile objects, subject to the disruptive effects caused by their internal starburst and by external tidal shear and ram pressure.

3.3. Gas removal by internal and external processes

The notable study of Ferrara & Tolstoy (2000) has shown that a dark matter poor low-mass galaxy may suffer a blow-away, i.e. a total disruption following the removal of all their gas content. However, as more recently noted by Recchi & Hensler (2013), the fate of the gas, as well as the strength of the stellar winds, and thus the ability of a dwarf to lose its metals, also depend on its initial structure and gas distribution. The most massive gas-rich star-forming TDGs (with total masses exceeding 10^8 $M_\odot$) are somehow protected from their internal feedback. On the other hand, they are still subject to external environmental effects. Among those, ram pressure may play a major role. The toy models and wind tunnel experiments made by Smith et al. (2013) suggest that the dragging of gas due to ram pressure may be prominent and even cause the disruption of the underlying stellar counterpart, and thus the destruction of TDGs. On the other hand the more realistic chemo-dynamical models of Ploeckinger et al. (2013) which include the effects of stellar winds, ram pressure as well as the external tidal field are more optimistic, suggesting that the long term survival of TDGs is possible. This work also implies that the efficiency of TDGs at injecting metals in the surrounding intergalactic medium may not be as high as previously thought.

3.4. Chemical tagging of TDGs

The M81 group, the inner regions of which are shown on Fig. 1, hosts at last 30 dwarf galaxies. Among those, 5 are considered as putative TDGs (Chiboucas et al. 2013), including the already discussed galaxy Holmberg IX. One of the criteria to identify TDGs among regular dwarfs, once independent from their parent galaxy, is their metallicity excess with respect to their mass (Duc et al. 2011). They are indeed made of pre-enriched material, and have inherited from their parents part of their metal content. A starburst-induced local chemical enrichment will further accentuate the excess. Oxygen abundances of TDGs range between half solar to solar. This chemical tagging has in particular been recently exploited by Sweet et al. (this volume) and Duc et al (2014, submitted) to identify Gyr old TDGs. Note however that whereas simulations predicting the chemical evolution of TDGs are already available, the detailed chemical analysis of real TDGs (measurement of abundance ratios of different elements) remains to be done. Direct observations of strong outflows from TDGs are also missing.

4. Conclusions: the limited role of collisions?

This review started with statements on the presumably important role of collisions on galaxy evolution in general, ISM/IGM enrichment in particular. The main responsible processes were discussed: local enrichment following extended or nuclear star formation episodes, radial mixing of the gas causing a flattening of the metallicity gradient.

The fact that collisions, in particular major gas–rich mergers of galaxies (addressed here), have a strong impact on their chemical properties does not imply that the chemistry of most galaxies is governed by collisions. In the recent years, following the discovery that most star-forming galaxies lie along a main sequence (in the star formation rate/efficiency versus mass plane), and that distant galaxies may have high SFRs without being involved in a merger, collisions have become less fashionable. Outflows and ISM/IGM enrichment may be driven by other processes, such as starbursts induced by the so called violent disk instabilities.

The specific role of tidal dwarf galaxies in the ISM/IGM enrichment – which was originally the topic assigned to my contribution – is still poorly understood. Models and recent simulations provide contradictory results. Some claim that TDGs are very fragile and do not survive internal and external processes. If this is the case, torn out TDGs will directly supply the surrounding medium with polluted material. Other models indicate that TDGs are robust and somehow manage to keep their material, despite the lack of dark matter. Thus paradoxically the more numerous they are, the less they will play a role in the enrichment of the intergalactic medium. Their number in the real universe is a subject of debate. The census of TDGs has started in the Local Group, where their presence remains controversial, and in nearby groups, in particular *in the M81 group, which has accompanied us in this review*.

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