STAR FORMATION REGULATION, GAS CYCLES AND THE CHEMICAL EVOLUTION OF DWARF IRREGULAR GALAXIES

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Abstract. Due to their low gravitational energies, dwarf galaxies are greatly exposed to energetical influences from internal and external sources. By means of chemodynamical models we show that their star formation is inherently self-regulated, that peculiar abundance ratios can only be achieved assuming different star-formation episodes and that evaporation of interstellar clouds embedded in a hot phase can lead to a fast mixing of the interstellar gas. Metal-enriched hot outflows can accrete onto infalling clouds by means of condensation leading to a large range of timescales for the self-enrichment of the ISM from local scales within a few tens of Myr up to a few Gyr for the large-range circulation. Infall of clouds is also required to explain abundance ratios of metal-poor galaxies at evolved stages because it reduces the metallicity altering only marginally the abundance ratios.

1 Introduction

Gas-rich dwarf galaxies are commonly thought to be characterized by a \textit{bursting} star formation (SF), namely, short episodes of intense SF rates separated by long periods of quiescence. An alternative scenario is the \textit{gasp}ing one, namely, long episodes of moderate SF rates separated by short periods of SF suppression. The presence of stars of intermediate age is apparently ubiquitous (e.g. Kunth \& Östlin 2000), therefore these objects are more evolved than previously thought. The chemical evolution of galaxies is strongly affected by the choice of the SF regime and by environmental effects, in particular gas infall. In this contribution, we will focus on the evolution of abundance ratios under different astrophysical assumptions and on the cooling and mixing timescales of freshly produced metals, a complex, very controversial and still unsolved problem (see e.g. Roy \& Kunth 1995; Tenorio-Tagle 1996; de Avillez \& Mac Low 2002 among others).

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2 Single gas-phase chemodynamical model of gas-rich dwarf galaxies

2.1 The chemical and dynamical evolution after instantaneous starbursts

An intense SF episode of short duration distributes the energetic and chemical feedback from massive stars in a few tens of Myr. If this is the first significant episode of SF, a large fraction of freshly produced metals can cool and mix with the surrounding ISM in a timescale of the order of a few $10^7$ yr. This is shown by single gas-phase chemodynamical models of dwarf irregular galaxies (dIrrs) (Recchi et al. 2001; 2002) and occurs essentially for two reasons. On the one hand, the thermalization efficiency of SNe exploding in a cold and dense medium is very small. A long time elapses before the expansion velocity of the supernova remnant (SNR) decreases to become equal to the local sound speed (time at which the cavity of the SNR and the external medium get in casual connection) and in this interval radiative losses reduce considerably the thermal budget of the SNR. On the other hand, a supershell which is not fast enough to create soon a break-out of the galaxy is subject to the growth of Kelvin-Helmholtz and Rayleigh-Taylor instabilities and to the development of large eddies. Thermal conduction has also time to spread the conduction front separating the cavity from the supershell. These phenomena favor the cooling of the metal-rich material inside the cavity and its mixing with the external unprocessed ISM. This implies that a significant fraction of the freshly produced chemical elements leaves quite soon (in $\sim 10-20$ Myr) the hot phase (where it is undetectable in the optical) and contributes to the observed metallicity of the galaxy, which therefore increases quite rapidly in the early evolution of the object.

2.2 Gasping or continuous star formation and consequences for the chemical evolution of galaxies

This non-bursting SF scenario is characterized by a much smoother energy release and therefore also the thermodynamical properties of the ISM change gently. Eventually a galactic wind arises after timescales of 100 Myr or more and at this point the accumulated energy of several generations of stars has carved a large cavity. Every subsequent generation of stars releases its energy in a hotter and more tenuous medium. The cooling timescale of this gas is much larger and also the occurrence of eddies or thermal instabilities is more unlikely. Therefore it is much more complicated for the gas released by late episodes of SF to cool down and mix with surrounding cold gas. In figs. 6 and 7 of Recchi et al. (2006), this effect is visualized for a model reproducing NGC 1569, one of the best studied proto-typical starburst dIrrs. It is clearly visible that the fraction of cooled ejecta from the last episode of SF is very large for a bursting model whereas it is negligible compared to the hot ejecta in a gasping model.

More importantly, these different behaviors change the chemical pattern of a galaxy substantially. For models reproducing the main properties of I Zw 18, one of the most metal-poor galaxies locally known, we have compared in Fig. 1 the
Fig. 1. Evolution of $12 + \log(\text{O/H})$ (top panel) and $\log(\text{N/O})$ (central panel) for models reproducing I Zw 18 with a gasping SF (solid line), with one (dotted line) or two (dashed line) instantaneous bursts. The SF history of the gasping model is represented by the shaded area in the bottom panel.

Evolution of O and N/O for a gasping model (whose SF history is sketched in the bottom panel) and models with one or two instantaneous bursts of SF (see Recchi et al. 2004). For this, only the metallicity of gas with temperatures below $2 \times 10^4$ K is considered. As expected, due to the fast cooling timescales of the ejecta, the bursting models are characterized by a fast change of the abundance ratios in short timescales. Gasping models show instead a continuous increase of the metallicity for about 120 Myr. Thereafter, the cooling timescale of the ejecta becomes so large that they cannot contribute anymore to the global chemical enrichment of the galaxy, therefore the metallicity and the abundance ratios do not change appreciably from this moment on. We notice in particular that, after the last burst occurring at 280 Myr, no increase of O or decrease of N/O (as it would be expected) is observed. In fact, almost all the ejecta produced by this burst are either carried out of the galaxy by a galactic wind or are released into a too hot phase, where they remain due to its very long cooling timescale.

3 Large-scale matter cycle in multi-phase chemodynamical models

dIrrs with high SF rates are often surrounded by large HI reservoirs with decoupled dynamics (e.g. NGC 4449, I Zw 18) or are suffering a collision with large
intergalactic H\textit{i} clouds (e.g. He 2-10, II Zw 40). This leads to the plausible assumption that SF is triggered and even enhanced to a burst by gas infall if the infalling H\textit{i} clouds replenish the consumed gas on a timescale shorter than that of self-regulating energy release by massive stars. Gas infall is observationally manifested for NGC 1569 where, from an extended and tidally disrupted H\textit{i} cloud complex (Stil & Israel 2003), a series of gas clumps falls in towards NGC 1569 (Mühle et al. 2003). This striking infall scenario leads to several consequences that can be studied in models and interpreted from observations. In particular, gas infall affects the outflow cycle of hot metal-enriched gas and the chemical abundance ratios (assumming that the infalling clouds have metallicities smaller than those in a galaxy).

Because of the coexistence of cold clouds enveloped by hot metal-rich gas and due to turbulence and the fragmentation of superbubble shells, the chemical elements freshly released by SNeII are mixed into the cool gas within the SF environment (see also Sect. 2.1). If the hot gas is able to evaporate the cold clouds and due to its overpressure a galactic mass-loaded outflow occurs (Hensler et al. 1999). Since these clouds contain elements from intermediate-mass stars of older stellar populations, e.g. carbon and nitrogen, the N/O ratio should represent this mixing effect. The cooling of hot gas enables its condensation onto infalling clouds and leads to their pollution with the elemental mix. The abundance patterns, however, become apparent only after the formation of H\textit{ii} regions.

The analyses of this matter cycle in a \textit{multi-phase} chemodynamical dIrr model of $10^9\ M_\odot$ baryonic mass in a $10^{10}\ M_\odot$ dark matter halo (Hensler 2001) show that $\sim$ 25\% of the metals produced in massive stars remain within the SF sites and lead to a local self-enrichment within 1 kpc on typical timescales in the range of 10 Myr. The remaining 3/4 of produced SNIa metals are carried away from the SF region by the superbubble expansion. Since the temperature of the hot gas decreases with its expansion, i.e. is lower at larger distances, the fraction of condensed hot gas and, by this, of the metal deposition in clouds increases outwards up to a distance of 15 kpc from the dIrr’s center.

Although the metals are hardly directly expelled from a dIrr by the galactic wind but incorporated into infalling clouds, the circulation timescale for the return of metals originating in the galaxy can last from 1 Gyr at 3 kpc to 10 Gyr from above 10 kpc (Hensler 2001). If one takes into account that widely distributed metal-enriched hot gas in dIrrs can be stripped off by the intergalactic medium or by tidal effects, still 50\% of the metals from SNeII are retained in this model and transferred to the cool gas within a distance of not more than 8 kpc. As a result, analytical studies and hydrodynamical models that investigate the expansion of hot SNIa gas alone as tracer of the metal dispersal, overestimate the total metal loss from the galaxy if small-scale mixing effects are neglected.

\section{The effect of gas infall on the element abundances}

In the N/O-O/H diagram dIrrs form a cloud with an appreciable amount of scatter around log(N/O) = -1.5 and over a range of 12+log(O/H) between 7 and
8.5. This regime is usually passed by evolving galaxies within their very early stages of evolution although the path can vary due to the SF timescales (Henry et al. 2000). Since the vast majority of dIrrs contains old stellar populations, the problem exists how to reach these low abundance values from an evolved state that is reached on the secondary production track of N. Under the assumption that dIrrs are young systems several authors allowed for starburst-driven galactic winds with selective element depletion, while others presented models that follow the assumption of abundance self-enrichment of the observed H\textsc{ii} regions. For a comprehensive discussion see Hensler et al. (2004).

On the reasonable basis of the infall scenario of pristine gas Köppen & Hensler (2005) explored the evolutionary path in the log(N/O) - 12+log(O/H) phase space when starting from an evolved state with a metal enrichment by former stellar populations. The main issue is that the path forms a loop at first to lower O/H values and back to the starting point via lower N/O ratios. The extent of the loop is related to the mass ratio of infalling to existing gas in the SF site. Since galaxies with smaller masses remain underdeveloped at lower log(N/O) - 12+log(O/H) values than more massive ones, the loop sizes are larger for low-mass galaxies. As a result, a sampling of all possible infall models therefore reproduces well the characteristic observed distribution (Henry & Worthey 1999) which cover an almost triangular regime with larger extension at lower N/O. Taking additionally a reasonable infall-triggered starburst into account the distribution (Fig. 2) changes not much in comparison with burst-less models (see figs. 18 and 20 in Köppen & Hensler 2005). In a very recent study Knauth et al. (2006) have also invoked gas infall as an explanation for the local interstellar N/O abundances.

Fig. 2. Location of dIrrs models with infall and starbursts in the log(N/O) - 12+log(O/H) diagram. For details see text.
5 Concluding remarks

The main results of our work can be summarized as follows:

- Short episodes of SF enrich the ISM in a timescale of a few tens of Myr.
- Long-lasting episodes of SF enrich gradually the ISM in a longer timescale. Any further episode of SF does not leave an appreciable imprint on the chemical evolution. In fact, the metals produced by these SF episodes are either directly carried out of the SF region, or they are released in a too hot medium and they do not have the chance to pollute the surrounding ISM.
- Multiphase chemodynamical models of dIrr galaxies show that $\sim 25\%$ of the stellar ejecta mix locally (within 1 kpc) on typical timescales of the order of 10 Myr, whereas the remaining metals undergo a longer cycle, via condensation onto clouds on timescales larger than 1 Gyr.
- The infall of metal-poor clouds changes the chemical evolution of dIrrs. In particular it forms loops in the O/H vs. N/O diagram, whose extension is related to the mass ratio of infalling to existing gas in the SF cloud. These loops account well for the observed N/O of metal-poor dwarf galaxies.

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References

- de Avillez, M.A., & Mac Low, M.-M. 2002, ApJ, 581, 1047
- Henry, D. & Worthey, G. 1999, PASP, 111, 919
- Henry, R.B.C., Edmunds, M.G., & Köppen, J. 2000, ApJ, 541, 660
- Hensler, G. 2001, ASP Conf. Ser. Vol. 245, eds. T. von Hippel et al., p. 401
- Hensler, G., Rieschick, A., & Köppen, J. 1999, in ASP Conf. Ser. Vol. 187, ed. J. Beckman & T.J. Mahoney, p. 214
- Hensler, G., Köppen, J., Pfenn, J., & Rieschick, A., 2004, IAU Symp. 217, eds. P.-A. Duc, J. Braine, & E. Brinks, p. 178
- Knauth, D.C., Meyer, D.M., & Lauroesch, J.T. 2006, ApJ, 647, L115
- Köppen, J. & Hensler, G. 2005, A&A, 434, 531
- Kunth, D., & Östlin, G. 2000, A&ARv, 10, 1
- Mühle, S., Klein, U., Wilcots, E. M., & Hüttmeister, S. 2003, ANS, 324, 40
- Recchi, S., Matteucci, F., & D’Ercole, A. 2001, MNRAS, 322, 800
- Recchi, S., Matteucci, F., & D’Ercole, A., & Tosi, M. 2002, A&A, 384, 799
- Recchi, S., Matteucci, F., & D’Ercole, A., & Tosi, M. 2002, A&A, 426, 37
- Recchi, S., Hensler, G., Angeretti, L., & Matteucci, F. 2006, A&A, 445, 875
- Roy, J.-R., & Kunth, D. 1995, A&A, 294, 432
- Stil, J.M. & Isreal, F.P. 2003, A&A, 392, 473
- Tenorio-Tagle, G. 1996, AJ, 111, 1641