Part 2. Origin

The Interstellar Medium at Low Redshift

Recycling Intergalactic and Interstellar Matter
IAU Symposium Series, Vol. 217, 2004
Pierre-Alain Duc, Jonathan Braine and Elias Brinks, eds.

Gas Mixing, Gas Cycles and the Chemical Evolution of Dwarf Irregular Galaxies

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Abstract. Dwarf galaxies are ideal laboratories to study influential effects on galaxy evolution. In particular, their gas-rich variant with very active star formation, starbursting dwarf irregulars, shows chemical and structural signatures that lead unambiguously to the conclusion that they are standing in a vital contact with their surroundings. Gas infall cannot only trigger star formation but also allows for a reduction of the metal content. On the other hand, active star formation ignites numerous supernovae type II which accumulate and can produce a galactic wind. This again depletes the metals pushing them into a gas mixing cycle with different timescales, locally of about 10 Myrs, but an galactic scales of at least 1 Gyr. This paper illuminates the different processes like gas infall and outflow and their effects on the chemical evolution, the star formation, and the gas mixing in dwarf irregular galaxies.

1. Introduction

Dwarf galaxies (DGs) serve as fundamental probes for understanding the evolution of galaxies in the context of cosmological models. On the one hand, they are invoked to trace the low-mass Dark Matter (DM) units and to act as building blocks for the accumulation of galaxy masses in the hierarchical CDM cosmology. On the other hand, their evolutionary paths from formation to their fading or even to their disappearance differ substantially. They seem to form at all cosmological epochs, by different processes, from different sources, and in different environments. Because of their low binding energy their evolution is strongly affected by internal and external energetic events thus leading to a wide variety of morphological types.

Dwarf irregular galaxies (dIrrs) are the most interesting DG types because they are still gas rich and differ largely in their parameters. As already described by their classification they are mostly irregularly structured with very bright centers and/or a patchwork of SF regions. In addition, their present SF rates show large variations from low to extraordinarily high values that cannot be maintained for a Hubble time, as e.g. in starbursts (SBDGs). The newly formed stellar associations are mostly very massive and compact, so-called super star clusters (SSCs).

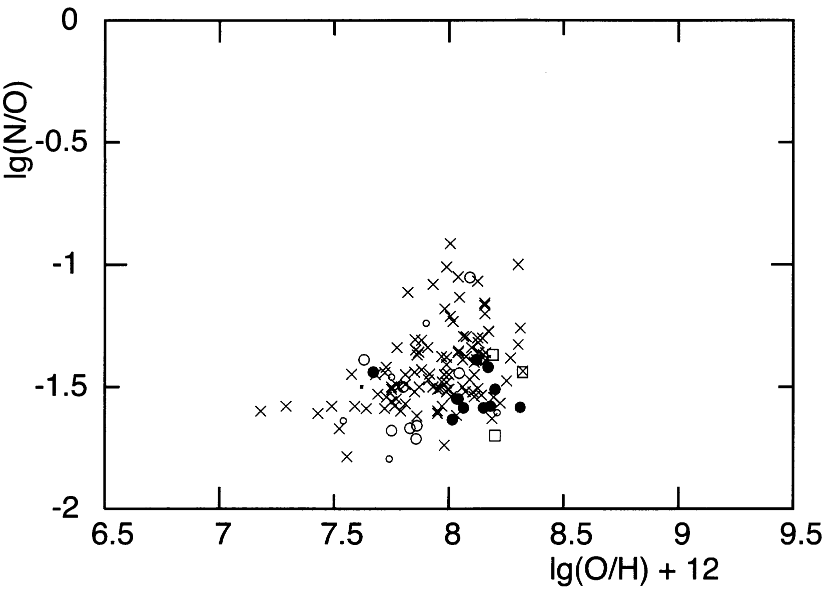

Figure 1. The log(N/O) and 12+log(O/H) observations of metal-poor dIrrs taken from the literature.

These two effects, namely, high SF rates and low metallicities obtrude the picture of dIrrs to be unevolved systems in the early stage after their formation. More detailed observations during the past years, however, have unveiled old underlying stellar components in most dIrrs like e.g. in NGC 1569 (Heckman et al. 1995) or NGC 1705 (Meurer et al. 1992; Tosi et al. 2001). There are two objects that can be denoted as really young, namely, I Zw 18 (Skillman et al. 1994; Aloisi, Tosi, & Greggio 1999; Hunt, Thuan, & Izotov 2003) and SBS 0355-52 (Izotov & Thuan 1999).

That dIrrs consist of the same or slightly higher gas fractions than giant spiral galaxies (gSs), mostly suffer the same SF efficiency and appear with a wide range, but lower metallicity Z than spirals, cannot be explained by simple models. When gas is consumed by astration, in simple models where timescale effects do not account, stellar element abundances have to follow a general analytical relation with the remaining gas content and according to their stellar yields (Pagel 1997). As demonstrated by Garnett (2002) and van Zee (2001), however, the effective yields of gas-rich galaxies decrease with smaller masses what means that their element abundances, particularly O measured in HII regions, are much smaller than those released by a stellar population and confined in a "closed box".

Furthermore, the abundance ratios of dIrrs are unusual. As already demonstrated by Pagel (1985) some dIrrs, though with O abundances below 1/10 solar, show also low N/O ratios of up to 0.7 dex smaller than in gSs, with a large scatter and no significant correlation with O/H (see Fig.1). Their regime of N/O–O/H values overlaps with those of HII regions in the outermost disk parts of gSs at around 12+log(O/H) = 8.0 ... 8.5 (van Zee, Salzer, & Haynes 1998a).

Two processes can reasonably reduce the metal abundances in the presence of old stellar populations: loss of metal-enriched gas or infall of metal-poor to even pristine intergalactic gas (ICM). This paper is aimed to consider these possibilities and their issues by different models.

2. Galactic winds

Only some fraction of these SBDGs are characterized by superwinds (Marlowe et al. 1995) or large expanding X-ray plumes which are driven by supernovae type II (SNeII) (see e.g. Hensler et al. 1998; Martin, Kobulnicky, & Heckman, 2002). On the other hand, if a SB drives a galactic wind it expels its fuel for subsequent events and can transform a gas-rich dIrr into a fading gas-poor system (Babul & Rees 1992) The formation of SN-driven winds in DGs are frequently studied under various but mostly uncertain conditions (Suchkov et al. 1994; Bradamante, Matteucci, & D'Ercole 1998; D'Ercole & Brighenti 1999; MacLow & Ferrara 1999). Some studies have raised doubts to whether the expanding Hα loops, arcs, and shells really allow gas expulsion from the galaxies because their velocities are mostly close to escape, but external gas tends to counteract. In addition, the possibility of sweeping the interstellar medium (ISM) out of these galaxies is questionable (Martin 1999; Ferrara & Tolstoy 2001). Even without external pressure, but under the restriction of radial symmetry in chemo-dynamical models of DGs (Hensler, Theis, & Gallagher 2003), significant amounts of gas can be kept bound even for high SF rates and lead to different SF regimes from single episodes to repeated events, by this, reproducing some major signatures of dwarf ellipticals (dEs) and dwarf spheroidals (dSphs).

3. Chemical Evolutionary Models of Dwarf Irregulars

From the adherent energy release of the stellar mass-loss processes, C and N are contributed by planetary nebulae from intermediate-mass stars to the warm cloudy gas, while O and Fe are predominantly added by means of SNeII or supernovae type Ia (SNeIa), respectively, to the million degrees hot phase. From simple assumptions the abundance ratios of particular elements from different sources, therefore, trace the energetic events and the lifetimes of their stellar progenitors.

This general differentiation e.g. between N and O pollution to the gas phases has therefore also led several authors to propose various chemical models which take the different lifetimes of the stellar progenitors into account and can successfully reach the observed N/O–O/H regime of DGs. Under the assumption that dIrrs are young systems e.g. Matteucci & Tosi (1985) and Marconi, Matteucci, & Tosi (1994), allowed for SB-driven galactic winds with selective element depletion and stated to be able to quantify even the number of SBs necessary for the reduction of O. Garnett (1990) and Pilyugin (1992) presented models that follow the assumption of abundance self-enrichment of the observed HII regions as it was at first proposed from observations by Kunth & Sargent (1986).

Nevertheless, Henry, Edmunds, & Köppen (2000, hereafter: HEK) demonstrated with the simple closed-box assumption and under the use of the most recent metal-dependent stellar yields that galaxies only in their early evolutionary stage pass the region of N/O vs. O/H observations where almost the full scatter of data can be explained by different SF timescales. While aging these galaxies reach the secondary-N production (SNP) track in the log(N/O) – 12-+log(O/H) diagram. The same results were visible in chemo-dynamical models of dIrrs during the first 2 Gyrs of evolution (Hensler et al. 2004). Compact narrow emission-line galaxies (abbreviated as CNELGs) that seem to represent similar starbursting objects at intermediate redshifts have already reached solar oxygen values but with an average log(N/O) by 0.3 to 0.4 dex lower than solar (Kobulnicky & Zaritzky 1999). The location of dIrrs on the SNP line is determined by their effective yield. And in the case of differential O loss, their evolutionary path in this diagram would go to the upper left, i.e. into a zone avoided by real objects.

Local Group dIrrs gather again around log(N/O) $\approx$ -1.5 but at 12+log(O/H) of almost 8.2, by this at the lower end of the SNP line (Skillman, Bomans, & Kobulnicky 1997).

For the present conditions of dIrrs this means: because they contain an old stellar population that has polluted the ISM with the elements under consideration and even with different effective yields due to gas loss by galactic winds, they must have passed the observed range of log(N/O) – 12+log(O/H) to the right-hand side.

In dEs and dSphs, which are devoid of gas, the moderate-to-low metallicities can only be understood if the SF has ceased due to the expulsion of the remaining gas reservoir. The repetitive SF epochs in some dSphs (Hodge 1989) can be only understood if some gas has been kept bound and fallen back (Hensler, Theis, & Gallagher 2003). That in the Carina dSph also a few SF events have occurred (Smecker-Hane et al. 1994) but did not lead to an increase of the metallicity, on the other hand, requires the infall of unprocessed and thus external gas.

4. The Chemical Evolution with Gas Infall

From more sensitive observations and refined data analyses there is growing evidence that dIrrs are enveloped by HI reservoirs (e.g. NGC 4449: Hunter et al. 1998; I Zw 18: van Zee et al. 1998b). Such gaseous halos would have two major effects, possibly fuelling high SF rates and aggravating supernova-driven outflows. There is a clear indication for gas infall from an HI reservoir in NGC 1569 (Stil & Israel 2003) where two massive star clusters formed over the last 50 Myrs (Aloisi et al. 2001). Another possibility for the ignition of SBs in dIrrs is just experienced by He 2-10 during its collision with an intergalactic gas cloud that produces several knots of SSCs (Kobulnicky et al. 1995).

If we follow with the same yield models and SF law as HEK but with various effective yields (1.0, 0.3, 0.1) the evolutionary tracks of dIrrs in the log(N/O) – 12+log(O/H) diagram and, in addition, allow after 13 Gyrs (as an extreme case) for an infall of $10^6 - 10^8\,M_\odot$ primordial gas clouds within 500 Myrs, the

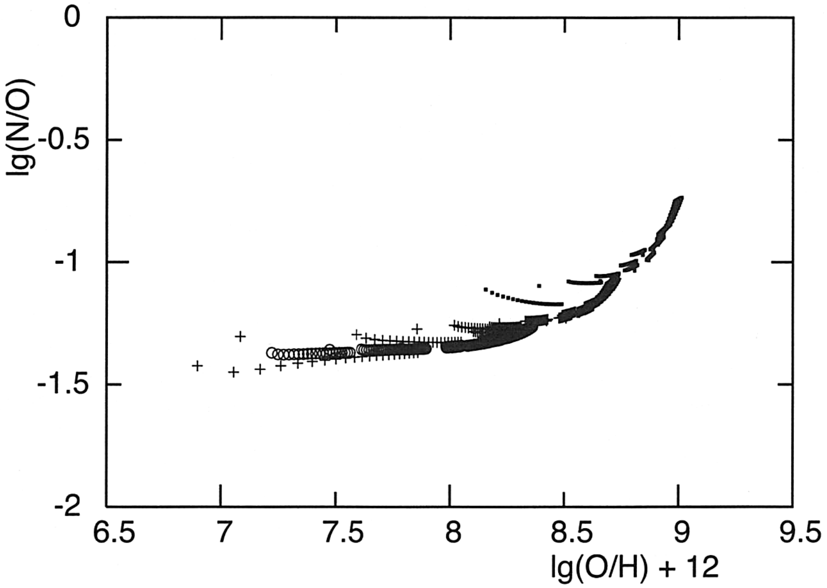

Figure 2. The evolutionary tracks with infall of primordial gas and for different effective yields (see text).

chemical evolution drives dIrr models back to the left. The tracks visible in Fig.2 (dots and crosses) are inevitably extended in O with a wider range for models of lowest effective yields what, on the other hand, can be translated to be the lowest masses. Since the tracks are mainly horizontal without loops as produced in models where primary O and secondary N are schematically disconnected (Hensler, Köppen, & Rieschick 1999), the scatter in N/O might be caused by different locations of the objects at the beginning of infall. The triangular region of observations (HEK and Fig.1) is produced because, roughly speaking, the fraction of infalling gas increases for galaxies of lower masses (Hensler & Köppen 2004).

5. Star-formation Rate vs. Infall

Since also gSs are exposed to infalling HI gas in the form of high-velocity clouds as observed directly within our Milky Way Galaxy (MWG), and because this infall rate is of the order of the SF rate one could be tempted to speculate that the SF in equilibrium is fine-tuned by gas infall or even enhanced for short infall events. As a first approach, we consider the system of time-dependent equations taking into account two gas phases, cool cloudy medium c and hot gas g, and two stellar components, massive stars s and the sum of long-living stars and remnants, denoted as r.

$$\dot{g} = \frac{\eta}{\tau} s + E_c - K_g$$
$$\dot{c} = -\Psi - E_c + K_g + A_c$$

$$\begin{aligned}
\dot{s} &= \xi\,\Psi - \tfrac{1}{\tau}\,s \\
\dot{r} &= (1-\xi)\,\Psi + \tfrac{(1-\eta)}{\tau}\,s \\
\dot{e}_g &= h_{SN}\,s - g^2\,\Lambda_0(T_g) + E_c\,b\,\tilde{T}_c - K_g\,b\,T_g \\
\dot{e}_c &= h_\gamma\,s - c^2\,\Lambda_0(T_c) - E_c\,b\,T_c + K_g\,b\,\tilde{T}_g - \Psi\,b\,T_c + b\,T_{A_c}\,A_c + \tfrac{1}{2}\,v^2\,A_c
\end{aligned}$$

All variables represent densities because we focus our analysis on a region of (500 pc)^3 representative for the ISM of the MWG disk in the solar vicinity. For the SF rate $\Psi = C_n\,c^n\,f(T)$ Köppen, Theis, & Hensler (1995) have shown that in a closed-box model an equilibrium situation is installed due to energetic self-regulation. Also for the gas phase transitions by condensation K_g and evaporation E_c a balance regulates the SF rate (Köppen, Theis, & Hensler 1998). As an external perturbation gas infall of cool gas c with a density rate given by $A_c := \frac{dM_c}{dV\,dt}$ is included here with its impact of infall energy on e_c. $\Lambda_0(T)$ is the temperature-dependent cooling function, ξ denotes the fraction of massive stars built from the SF rate and τ is their averaged lifetime until they explode as SNeII and release the fraction η of the stellar mass s to the hot gas. In the energy equations $(\dot{e}_g, \dot{e}_c)$ h_{SN} and h_γ are dedicated to account for heating by massive stars, SN explosions and radiation, respectively. The gas temperatures signed by a tilde are reflecting the peculiar temperatures of the exchanged gas components.

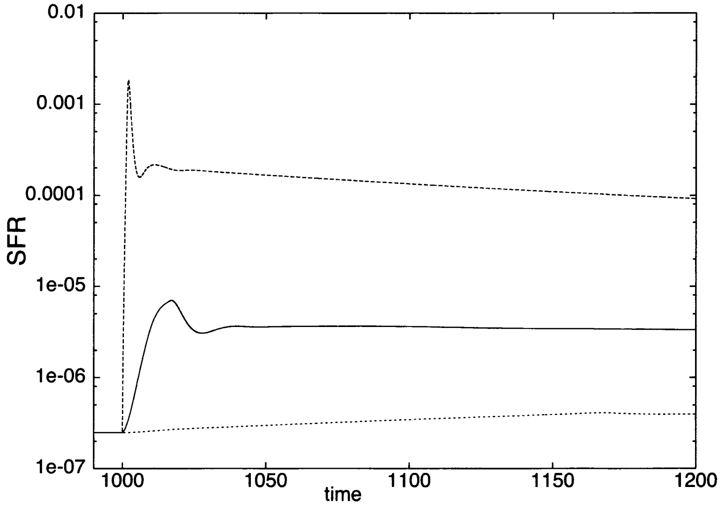

Figure 3. Star-formation rate in $M_\odot/(pc^3$ Myrs) enhanced by clouds of 10^4 (dashed), 10^5 (full), 10^6 (dotted) $M_\odot$ falling in with 10 km/s.

The calculation starts after an equilibrium is adjusted for this region under consideration, here after 1000 Myrs. Since the results are discussed quantitatively in a forthcoming comprehensive paper (Pflamm, Hensler & Köppen 2004) here we wish to consider the SF reaction to gas infall qualitatively. As a quick illustration Fig.3 shows that the SF-rate density increases immediately with the infall. Since the clouds have Jeans masses their mean density is larger for smaller masses, i.e. the $10^6\,M_\odot$ cloud has a 100 times larger radius than $10^4\,M_\odot$ and thus needs at constant infall velocity 100 times longer. For the $10^4\,M_\odot$ cloud the infall duration at 10 km/s amounts to 1.6 Myrs and is connected with a steep increase of the SF rate by almost 4 orders of magnitude with respect to the initial equilibrium value. This peak is reached only for a very tiny timescale, while the subsequent SF rate still remains high with a factor of 1000 and declines to the equilibrium state over the next few billion yrs. For a cloud with $10^5\,M_\odot$ the infall takes 16.2 Myrs with a SF rate increasing by a factor of 30 higher. Because of its low density, the $10^6\,M_\odot$ cloud raises the SF rate only smoothly over 162 Myrs and then levels off at almost the equilibrium value.

Since the model is dealing with an isolated region the inserted overpressure by stellar energy release during a SB, that would otherwise be relaxed by an expansion of hot gas, the subsequent SF evolution here could be falsified. The results should therefore be treated with caution and only provide a qualitative insight into the triggering of SF by cloud infall.

6. Gas Mixing between Infall and Outflow

In reality the above-mentioned SBDGs can be characterized by both infalling HI gas and expanding hot gas bubbles. Because of the local coexistence of both gas phases and due to the turbulence and fragmentation in superbubble shells the freshly released SNII elements are mixed into the cool gas. We have traced the path of SNII elements in a $10^9\,M_\odot$ chemo-dynamical dIrr model (described in Rieschick & Hensler 2003) and analysed with respect to the local gas mixing and metal transport from the hot into the cool gas phase. The results in Fig.4 show that almost 25% of the metals produced in massive stars are deposited close to the SF sites themselves and, by this, lead to a local self-enrichment within 1 kpc on typical timescales in the range of 10 Myrs. The remaining 3/4 of produced SNII metals are carried away from the SF region by the expansion of hot superbubble gas. Nevertheless, this has incorporated evaporated clouds (Hensler et al. 1999). Since the clouds also consist of elements from intermediate-mass stars of an older population, i.e. carbon and nitrogen, the N/O ratio of subsequently emerging HII -regions is determined by this mixing effect. Because of the (at least adiabatic) cooling of hot gas, its condensation onto infalling clouds leads to their pollution. From Fig.4 one can discern that this amount of metal deposition onto clouds increases reasonably with distance according to the growing cooling and reaches up to a distance of 15 kpc from the dIrr's center.

Although the metals are thus not directly expelled from a dIrr by the galactic wind but incorporated into infalling clouds, the circulation timescale for the metal enrichment via condensation and return in clouds can last from 1 Gyr at 3 kpc to 10 Gyrs from above 10 kpc (Fig.5). This is due to the low inflow velocities of a few km/s only that are caused by the permanent compensation of the gravitational acceleration of clouds by means of outflowing gas. If one takes into account that widely distributed gas in dIrrs can be stripped off by the ICM or by tidal effects because it is only loosely bound, e.g. still 30% of the metals from SNeII are transferred to the cool gas within a distance of 5 kpc and thus falling back. Thereby, hydrodynamical models that investigate the expansion of hot SNII gas alone as tracer of the metal dispersal, but neglect small-scale mixing effects, overestimate the total metal loss from the galaxy (Tenorio-Tagle 1996);

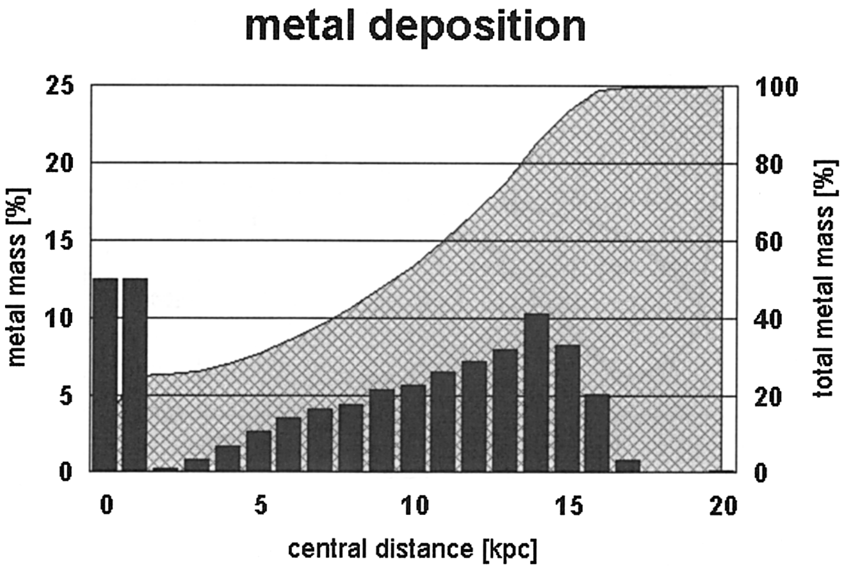

Figure 4. Local metal deposition from hot supernova type II gas that expands as galactic wind in a $10^9\,M_\odot$ dIrr chemodynamical model (Rieschick & Hensler 2001). The columns of histogram are evaluated on the left-hand scale and reveal the local fraction, while the accumulated deposition is displayed as grey area (right-hand scale). For details see text.

local mixing between gas phases by means of turbulence and condensation needs only several ten Myrs.

7. Conclusion

Because of their low gravitational energies dwarf galaxies are strongly exposed to energetic influences from internal and external sources. Since there is striking evidence that at least some of the actively SF dIrrs are affected by gas infall while dSphs must have lost their gas content before using it up by SF, the evolution of low-mass galaxies is intimately coupled with the environmental interference. Not only gas infall from the ICM, but also gas exchange by means of galactic outflows, stripping of halo gas in a relatively moving ICM as well as tidal effects are thus most important influences on the evolution of DG but also for more massive ones.

We have seen for a few special situations collected in this paper to what extent e.g. the chemical abundances and the SF rate will be affected by short episodes of infalling clouds. Furthermore, gas phases are neither dynamically nor energetically decoupled but exchange momentum, energy and gas. In particular, gas mixing processes determine the timescales for recycling of the ISM and its interplay with the ICM and must be investigated in full details.

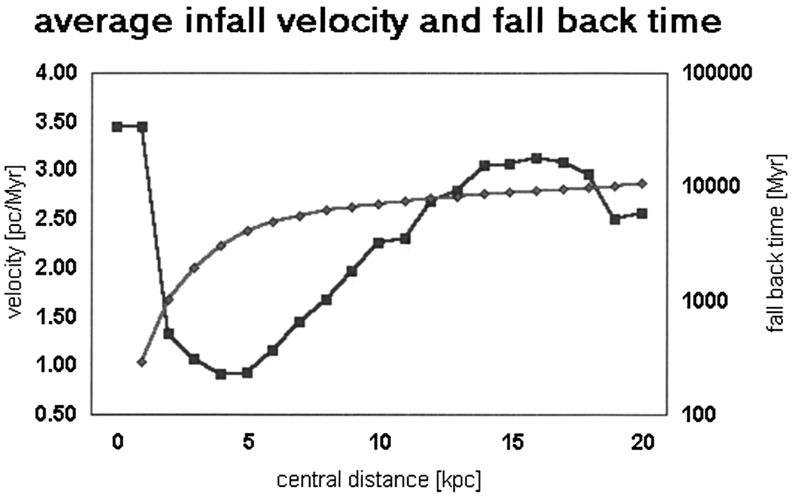

Figure 5. Mean infall velocity of clouds (thick line, left scale) from an HI reservoir in a $10^9\,M_\odot$ dIrr chemodynamical model (Rieschick & Hensler 2003) and the corresponding fall-back time of metals (grey line, right scale) produced by a former generation of massive stars. The metals are expelled from the dIrr by a galactic wind, condensed on the infalling clouds, and returning smoothly incorporated into the clouds.

Acknowledgments. Parts of this project are supported by the Deutsche Forschungsgemeinschaft (DFG) under grants no. HE 1487/23 (AR). GH acknowledges financial support by a DFG travel grant no. HE 1487/31 for the attendance of the GA2003 in Sydney and thanks the organizers of this Symposium for their invitation.

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