ABOUT THE EVOLUTION OF DWARF SPHEROIDAL GALAXIES

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Abstract. We present 3D hydrodynamic simulations aimed at studying the dynamical and chemical evolution of the interstellar medium in dwarf spheroidal galaxies. This evolution is driven by the explosions of Type II and Type Ia supernovae, whose different contribution is explicitly taken into account in our models. We compare our results with available properties of the Draco galaxy. Despite the huge amount of energy released by SNe explosions, in our model the galaxy is able to retain most of the gas allowing a long period (> 3 Gyr) of star formation, consistent with the star formation history derived by observations. The stellar [Fe/H] distribution found in our model matches very well the observed one. The chemical properties of the stars derive from the different temporal evolution between Type Ia and Type II supernova rate, and from the different mixing of the metals produced by the two types of supernovae. We reproduce successfully the observed [O/Fe]-[Fe/H] diagram.

1 Introduction

Due to their proximity, galaxies of the Local Group (see Mateo 1998, Grebel 2006 for a review) offer an unique opportunity to study in detail their structural properties, formation and chemical evolution.

In particular, the distribution of the local galaxies shows the clustering of dwarf ellipticals and dwarf spheroidal (dSphs) around the dominant spirals galaxies (Milky Way and Andromeda). Dwarf spheroidals are the least massive galaxies known, but yet, their velocity dispersions imply mass to light ratios as large as

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100 M⊙/L⊙. This is usually explained assuming that these systems are dark matter dominated. Actually, in the past few years both observational evidences (e.g. Kleyna et al. 2002, Lokas 2002, Walker et al. 2006) and theoretical works (e.g. Kazantzidis et al. 2004, Mashchenko et al. 2005) confirm the possibility that these galaxies are relatively massive bounded system with virial masses in the range 10⁸ − 5 × 10⁹ M⊙. Such galaxies are very metal poor and lack of neutral hydrogen and recent star formation. Thus they were initially believed to be very similar to Galactic globular clusters and to have a very simple star formation history (SFH). Recent studies have shown, instead, that these systems are much more complex, with varied and extended SFHs. High resolution spectroscopy of several dSphs showed the presence of a wide range in metallicity (Harbeck et al. 2001). For example, abundance analyses of stars belonging to Draco and Ursa Minor have shown values of [Fe/H] in the range −3 ≤ [Fe/H] ≤ −1.5 (Shetrone et al. 1998, 2001) with a mean value in the interval −2.0 ≤ ⟨[Fe/H]⟩ ≤ −1.6, depending on the authors (e.g. Shetrone et al. 2001, Bellazzini et al. 2002).

The above ranges are consistent, for some dSphs, with a single period of star formation extended in time for a few Gyr (e.g. Mateo 1998, Dolphin 2002). As a further hint of long SFH Shetrone et al. (2001) found that their observed dSphs have [α/Fe] abundances that are ∼ 0.2 dex lower than those of Galactic halo field stars in the same [Fe/H] range. This suggests that the stars in these systems were formed in gas pre-enriched by Type II supernovae (SNe II) as well as by Type Ia supernovae (SNe Ia), and star formation must thus continue over a relatively long timescale in order to allow a sufficient production of iron by SNe Ia.

Given the small dynamical mass inferred for dSphs, the interstellar medium (ISM) binding energy is small when compared to the energy released by the SNe II explosions occurring during the star formation period; for instance, as shown in the next section, in a dSph like Draco the baryonic matter has a binding energy of ∼ 10⁵³ erg, while the expected number of SNe explosions in the past was 10³ − 10⁴, realising an energy much larger than the binding energy. It is thus quite puzzling how the ISM can remain bound long enough to allow such a long star formation duration. Infact, contrary to SNe II, SNe Ia are poor producers of oxygen, great producers of iron, and start to explode after longer time scales; thus stars with low [O/Fe] indicate long SFHs.

Motivated by the above arguments, in this paper we explore the possibility that dSphs formed stars at a low SFR for a long period. To compare our results with observations, we have tailored our models on the Draco galaxy: this galaxy is supposed to have experienced a star formation lasting for 3-4 Gyr, and which essentially ceased 10 Gyr ago (e.g. Mateo 1998). Obviously, our results may be confronted with other dSphs which are strongly dark matter dominated and have similar SFHs as, e.g., Ursa Minor (Mateo 1998).

We run a number of three-dimensional (3D) hydrodynamical simulations to study the dynamical and chemical evolution of this system, following an assumed SFH. A special attention is paid to the influence of both SNe Ia and SNe II on the chemical enrichment of the new forming stars.
Fig. 1. Logarithm of the density distribution (g cm$^{-3}$) of the ISM in the $z = 0$ plane at different times. The first, second, third and fourth panels represent snapshots of the gas after a time interval $\Delta t = 15$ Myr, 30 Myr, 50 Myr and 80 Myr from the occurrence of the latest instantaneous burst. Distances are given in kpc. The grey scale map ranges from -26.5 (black) to -24.5 (white).

2 Model and discussions

We start our simulations with the ISM in hydrostatic equilibrium in the dark matter halo potential well. Although the stellar contribution to the gravitational potential well is neglected, we approximate the observed stellar distribution in Draco with a King profile with a mass content $M_\ast = 5.6 \times 10^5 M_\odot$. The stellar distribution is important to estimate (from the observed mass-to-light ratio) the dark matter halo properties and properly locate the SNe explosions. More details on the model construction can be found in Marcolini et al 2006. One of the basic assumptions of the model is that the dark matter halo extends beyond the stellar component ($R_\ast = 650$ pc) of the system (the mass of the dark matter halo at 1.2 kpc is $6.2 \times 10^7 M_\odot$). The initial gas mass is $M_{\text{ISM}} = 0.18 M_\odot$, which corresponds to the baryonic fraction given by Spergel et al. (2006).

Here we focus on a model in which we assumed that stars form in a sequence of 25 instantaneous bursts separated in time by 120 Myr. We further assume that a single SN II explodes for each 100 $M_\odot$ of formed stars, reaching the total number of 5600 at the end of the simulation (3 Gyr). The SNe II explode at a constant rate for 30 Myr (the lifetime of a 8 $M_\odot$ star, the less massive SN II progenitor) after the occurrence of each burst, while SNe Ia rate follows the prescription of Matteucci & Recchi 2001 (see Marcolini et al. 2006 for further details).

Figure 1 shows that as the SNe II start to explode, a large fraction of the central volume is filled by the hot rarefied gas of the SNRs’ interior, while the dense SNRs’ shells form dense cold filaments after colliding one with another. Once the SNe II stop to explode the global cavity collapses and the ISM goes back into the potential well; this happens nearly 30-40 Myr after the last SN II explosion. Note that the initial binding energy of the gas $E_{\text{bind}} \sim 8.3 \times 10^{52}$ erg is lower than the total energy $2.24 \times 10^{53}$ erg released by the SNe II after a single burst. The simulation thus shows that the radiative losses are substantial and prevent the evacuation of the gas, as shown in Fig. 1.
After 120 Myr a central high density gas region of the same size of the stellar volume is recovered, although turbulences and inhomogeneities are now present (see Fig. 1, fourth panel). A second burst of star formation then occurs leading to a second sequence of SN II explosions. The gas undergoes a new cycle of merging bubbles which eventually collapse again.

The influence of the SN Ia explosions on the general hydrodynamical behaviour of the ISM is not very important because during a cycle of SN II explosions no more than 8-9 SNe Ia occur, only ∼ 4% of the SN II number. Despite their little importance from a dynamical point of view, the role of SNe Ia is very relevant for the chemical evolution of the stars. The simulation shows that while the SN II ejecta become more and more homogeneous with time as the turbulence diffuse it, the SN Ia ejecta appear to be distributed less homogeneously; the reason for this is the low SNe Ia rate.

We point out that during the entire evolution the fraction of the SN ejecta present inside the stellar region remains very low (∼ 18% after 3 Gyr). This is the amount of metals which contributes to the metallicity of the forming stars. A large fraction of the ejecta is pushed at larger distances by the continuous action of the SN explosions. Figure 2 shows the [Fe/H] distribution function (MDF) of our simulated long-lived stars (with mass ≤ 0.9 M⊙), i.e. the mass fraction of these stars as a function of their [Fe/H]. At the end of the simulation we obtain a mean value of ⟨[Fe/H]⟩= −1.7 with a spread of ∼ 1.5 dex, in reasonable agreement with observations (e.g. Shetrone et al. 2001, Bellazzini et al. 2002), while the distribution maximum occurs at [Fe/H]=−1.6. Note that stars with [Fe/H] ≥ −1.4 (the high metallicity tail in Fig. 2) are particularly enriched by SN Ia ejecta and formed in the (relatively) small volume occupied by SN Ia remnants. This is particular evident in Fig. 2 (right panel) where we show the final [O/Fe]-[Fe/H] diagram. The open circles form a statistically representative sample of the stellar distributions in the [O/Fe]-[Fe/H] diagram. The plateau at [O/Fe]∼0.35 at low [Fe/H] is representative of the [O/Fe] value in SNe II ejecta, because the contribution of SNe Ia becomes important after a longer time scale. Indeed the small negative gradient of the plateau is due to the slowly growing contribution in the Fe enrichment by SNe Ia (which contribute only marginally to the Oxigen
production). The sharply decreasing branch at higher [Fe/H] is due to stars formed in the regions of ISM recently polluted (mostly by iron) by SNe Ia. A glance at Fig. 2 shows that the stars on the decreasing branch populate the MDF high [Fe/H] tail, while the majority of the stars occupies the high [Fe/H] edge of the plateau in the [O/Fe]-[Fe/H] diagram. We point out that our representative stellar sample is in reasonable agreement with the stars observed by Shetrone et al. (2001).

2.1 Other models

Here we describe the evolution of two models quite similar to the reference model (described above). Model B has the same SFH but differs in the dark matter content \((2.2 \times 10^7 \, M_\odot)\) and ISM mass \((4 \times 10^6 \, M_\odot)\) in order to preserve the cosmological ratio between the amount of baryonic and non-baryonic matter. Model C has the same properties of the reference model but differs in the duration \((\leq 1 \, \text{Gyr})\) and intensity \((10 \, \text{bursts})\) of SFH.

Model B loses all its gas in a period too short \((\leq 250 \, \text{Myr})\) to be consistent with the longer SFH of Draco. We point out that this effective gas removal is mainly due to a less efficient radiative cooling (due to the lower density of the gas) rather than to the shallower galactic potential.

Model C, instead, retains its gas for a longer time, and is able to form stars up to 900 Myr, consistently with recent cosmological simulations (e.g. Ricotti & Gnedin 2005, Kawata et al. 2006) before loosing the ISM via a galactic wind. This model shows \(\alpha/Fe \sim 0.1 \, \text{dex}\) higher than the value of the reference model because of the lower number of SN Ia explosions. However, although its chemical properties (both the AMD and the [O/Fe]-[Fe/H] diagram) are still in marginal agreement with observations, we belive that the star formation duration must be longer than \(\sim 1 \, \text{Gyr}\). Infact, Fenner et al (2006) find that only long SFHs (of the order of several Gyr) are able to reproduce the Ba/Y ratio because the stars must form over an interval long enough for the low-mass stars to pollute the ISM with s-elements.

3 Conclusion

We presented 3D simulations of a forming dSph resembling the Draco galaxy. With our assumptions, in our reference model the galaxy never gets rid of its gas (due to the huge efficiency of radiative cooling despite the low metallicity of the gas) and the star formation can last for several Gyr (as suggested by observations). This in turn implies the need of an external mechanism to remove the gas and stop the star formation, such as gas stripping (e.g. Marcolini et al 2003, only stripping, and 2004, stripping+SN feedback) and/or tidal interaction with the Galaxy (Mayer et al. 2006). Indeed, ram pressure due to gaseous haloes of the Milky Way and M31 is belived to explain the observed correlation between stellar content and galactocentric distance of dwarf galaxies (van den Bergh 1993). We are now running simulations of forming dSphs interacting with the Milky Way.
halo in order to understand whether the combined action of SNe feedback and ram pressure stripping can help in depriving these systems of gas.

Although the SN ejecta remain gravitationally bounded during the star formation, yet only a low fraction (∼ 18%) stays in the region where star forms. This effect mimics the assumption of metal removal by galactic winds in chemical evolution models. Our model succeeds in reproducing the [Fe/H] distribution of the stars. In agreement with observations, we find a mean value ⟨[Fe/H]⟩ = −1.7 with a spread of ∼ 1.5 dex. We can also satisfactorily reproduce the observed [O/Fe] vs [Fe/H] diagram. The origin of the break in this diagram, in our interpretation, is due to the low value of the porosity of SN Ia remnants. Indeed, given the low SN Ia rate, these remnants are located quite apart one from another, and the iron ejected by SNe Ia is distributed rather inhomogeneously through the stellar volume. As a consequence, stars forming in the (relatively small) volume occupied by SN Ia remnants have a ratio [O/Fe] lower than those forming elsewhere.

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