Neutral hydrogen in galactic fountains

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ABSTRACT

Simulations of an isolated Milky Way-like galaxy, in which supernovae power a galactic fountain, reproduce the observed velocity and 21-cm brightness statistics of galactic neutral hydrogen (H I). The simulated galaxy consists of a thin H I disc, similar in extent and brightness to that observed in the Milky Way, and extra-planar neutral gas at a range of velocities due to the galactic fountain. Mock observations of the neutral gas resemble the H I flux measurements from the Leiden–Argentine–Bonn H I survey, including a high-velocity tail which matches well with observations of high-velocity clouds. The simulated high-velocity clouds are typically found close to the galactic disc, with a typical line-of-sight distance of 13 kpc from observers on the solar circle. The fountain efficiently cycles matter from the centre of the galaxy to its outskirts at a rate of around 0.5 M⊙ yr⁻¹.

Key words: methods: N-body simulations – ISM: clouds – galaxies: ISM.

1 INTRODUCTION

Radio observations of the 21-cm hydrogen emission line reveal that the Milky Way (MW) contains a thin H I disc surrounded by a population of ‘clouds’ with velocities incompatible with models of galactic rotation, yet apparently not part of the Hubble flow either (Muller, Oort & Raimond 1963). The nature of these ‘high-velocity clouds’ (HVCs) remains somewhat unclear, mostly because it is difficult to determine their distances and hence infer physical properties.

Observations of stars with known distances along the line of sight to a HVC can be used to constrain the distance to the cloud, by testing whether or not it is detected in absorption in the stellar spectrum. Whether SNe explosions can start a galactic fountain has been investigated both theoretically and numerically (Shapiro & Field 1976). Gas from the galactic disc rises buoyantly after being heated by supernovae (SNe), becomes thermally unstable and cools radiatively into neutral clouds. Once the clouds are dense they fall back ballistically on to the disc, and are seen as the HVCs. Whether SNe explosions can start a galactic fountain has been investigated both theoretically (Kahn 1998) and through numerical simulations (Avillez 1998; Avillez & Berry 2001).

Blitz et al. (1999; see also Braun & Burton 1999) suggest that some HVCs are neutral gas associated with the numerous dark matter substructures seen in simulations of haloes of galaxies and groups of galaxies. Such HVCs are at large distances (≥40 kpc) from the galactic centre, and distributed throughout the local group. Connors et al. (2006) report the detection of H I clouds in fully cosmological Λ cold dark matter (ΛCDM) simulations of galaxy formation, and their HVCs are reminiscent of Blitz et al.’s clouds. Maller & Bullock (2004) discuss how a population of clouds at distances of ~150 kpc may result from the halo gas becoming thermally unstable. Given the rich variety of HVC properties, it seems likely that more than one of the above models, with an additional component resulting from tidal interactions (e.g. Ferguson et al. 2006), is required to explain the full cloud distribution. In this Letter we perform numerical simulations of star formation in an isolated galaxy halo to investigate the effect of supernova feedback.
MW-like galaxy, in which SNes power a galactic fountain. We analyse the simulation in terms of mock H I observations and demonstrate they reproduce many of the observed features of the H I disc and its HVCS.

This Letter is structured as follows. In Section 2 we provide details of the numerical scheme used in our investigation, and in Section 3 we present a comparison between our simulations and the distribution of galactic H I.

2 NUMERICAL METHOD

2.1 Star formation and feedback model

The star formation and feedback prescription used in the simulations is described in detail by Booth, Theuns & Okamoto (2007, hereafter BTO07); here we briefly review its main features. The scheme treats the interstellar medium (ISM) in terms of three distinct but interacting components: cold ($T < 10^2$ K) molecular clouds surrounded by a warm ($T < 10^4$ K) ambient phase in the disc, interspersed by a hot ($T \sim 10^5$ K) tenuous phase that extends into the halo, and is powered by SNes. Gas is cycled through these phases by a number of processes.

Conversion of gas to stars is regulated by the rate at which molecular clouds form and get destroyed. Clouds form from thermally unstable ambient gas and are destroyed directly by feedback from massive stars, and indirectly through thermal conduction. Gas cooling is due to Compton and line cooling, using interpolation tables generated with CLOUDY (Ferland et al. 1998). Feedback in the ambient gas phase cycles gas into a hot galactic fountain or wind.

We model the ambient and hot gas phases hydrodynamically using smoothed particle hydrodynamics (SPH, Gingold & Monaghan 1977; Lucy 1977) as implemented in the GADGET2 simulation code (Springel, Yoshida & White 2001; Springel 2005). Motivated by the fact that we cannot resolve the Jeans mass of the molecular gas, the clouds are modelled using ‘sticky particles’ that move ballistically through the ambient gas, but may coagulate when colliding. When such a cloud has built up enough mass through accretion and coagulation to form a giant molecular cloud (GMC), it collapses into stars, which then destroy the GMC through stellar winds and SN explosions.

BTO07 show that this model produces a multiphase medium with cold clouds, a warm disc, hot SN bubbles and a hot, tenuous halo, similar to that observed in spiral galaxies. The star formation rate, surface H I density, molecular fraction and molecular cloud mass spectrum of simulated galaxies match closely those observed in the MW.

2.2 Model galaxy

The initial conditions for our MW-like galaxy are generated using a publicly available program, GALACTICS (Kuijken & Dubinski 1995), which generates a near-equilibrium galaxy consisting of an approximately exponential disc, a bulge and a (dark matter) halo, using collisionless particles. The bulge, disc and halo have masses in the ratio 0.31:0.00:28.27 (giving a baryon fraction of 0.3 times the universal value). The total mass of the system is $2.21 	imes 10^{12} M_{\odot}$ and the circular velocity at the solar radius, $r = 8.5$ kpc, is $\sim 220$ km s$^{-1}$.

We convert 10 per cent of the disc particles into SPH particles using collisionless particles. The bulge, disc and halo have masses in the ratio 0.31:1.00:28.27 (giving a baryon fraction of $0.31:1.00:28.27$). Motivated by the similarity to that observed in spiral galaxies, we present a comparison between our simulations and the distribution of the numerical scheme used in our investigation, and in Section 3 we present a comparison between our simulations and the distribution of galactic H I.

2.3 Mock H I observations

We assume that the H I fraction of the ambient gas is set by the balance between photoionization, collisional ionization and recombinations, which we compute using CLOUDY (Ferland et al. 1998), imposing the ultraviolet background at redshift $z = 0$ given by Haardt & Madau (2001). This H I gas can be detected by its hyperfine emission line (Van de Hulst 1945). A hydrogen atom in its ground state has higher energy when the spins of proton and electron, $J_z$ and $J_e$, are parallel than when they are anti-parallel. Spontaneous transitions to the lower energy state occur at a rate governed by the Einstein coefficient, $A_{10} = 2.85 	imes 10^{-15}$ s$^{-1}$, and result in the emission of a ‘21-cm photon’ of wavelength $\lambda = 21.11$ cm $= c/\nu$. For the densities, $n_H$, and temperatures, $T$, relevant to the ISM, the typical time $\tau$ between collisions, $\tau \sim 100 \times (n_H/cm^{-3})^{-1} (T/10^4 K)^{-1/2}$ yr, is much shorter than the spontaneous 21-cm transition time-scale, $\tau_{1/2} = 10^{-9}$ yr, and so collisions keep the levels of the low and high states, $n_0$ and $n_1$, in the ratio $n_1 = 3n_0$. The mean emission rate of 21-cm photons per neutral hydrogen is then given by $A_{10}n_1 = (3/4)A_{10}$. The 21-cm flux of a cloud with neutral hydrogen mass $M_{\text{HI}}$ at distance $D$ is

$$F = \frac{(3/4) A_{10} (M_{\text{HI}}/m_H) \hbar \nu}{4\pi D^2} \approx 2 \times 10^{-19} \frac{M_{\text{HI}}}{M_{\odot}} \left( \frac{1 \text{kpc}}{D} \right)^2 \text{erg cm}^{-2} \text{s}^{-1}$$

(1)

(see e.g. Spitzer 1978). In radio astronomy, this is quoted in terms of the line flux, $\int S(\nu) d\nu$, with $S(\nu)$ expressed in Jy and the line width in km s$^{-1}$, $F = \int S(\nu) d\nu = \int S(\nu)/(\nu/c) d\nu$, hence (Wakker & van Woerden 1991)

$$\int \left[ \frac{S(\nu)}{\text{Jy}} \right] \left( \frac{d\nu}{\text{km s}^{-1}} \right) = \frac{1}{F} \frac{1}{\nu} \frac{c}{\text{km s}^{-1}}$$

(2)

$$F = \frac{1}{0.235 M_{\odot}} \left( \frac{\text{kpc}}{D} \right)^2.$$

The 21-cm ‘brightness temperature’, $T_B$, of an object is defined as the temperature at which a blackbody emits the same flux. The conversion from flux to brightness temperature is then given by $T_B/S = R$, where the telescope-dependent conversion factor that we use is $R = 0.158$ K Jy$^{-1}$ in order to match the observational survey against which we are comparing our results (Hulsbosch & Wakker 1988). To compute the simulated H I flux, we place an observer in the simulated galaxy and evaluate the net flux received by an ideal radio telescope with a beam size $\theta$. For a single SPH particle at position $r$, the fraction $dm/rm$ of mass that falls within the beam at distance between $r$ and $r + dr$ is

$$dm/rm = \int_{r}^{r+dr} 2\pi r^2 (\cos \theta - 1) dr J W(|r' - r|, h),$$

(4)
where \( h \) is the smoothing length of the particle, and \( W \) is the SPH kernel. The total flux received from this particle is computed from equation (1), and is represented by a Gaussian emission line centred at velocity \( v \cdot r/r' \) with width \( \sigma = (k_B T m_h)^{1/2} \), where \( m_h \) is the mass of a hydrogen atom. The total spectrum is obtained by integrating over \( dr \) and summing over all particles.

Simulations have been performed at two different mass resolutions to ensure that resolution effects do not affect our results. Observations have been repeated for a number of observers along the solar circle, and at times spanning a period of 1 Gyr. We use these observers to compute error bars on the mock observations. The distribution of \( \text{H}_\text{I} \) at galactic latitudes, \( b \), greater than \( 20^\circ \) does not depend strongly on the time at which observations are made, showing that our results do not represent a transient feature. Within the galactic disc \( (b < 20^\circ) \) the mean brightness temperature of the gas decreases slowly over time as the gas disc is converted into stars.

3 RESULTS AND DISCUSSION

The all-sky 21-cm brightness distribution of the simulated galaxy looks remarkably similar to the observed \( \text{H}_\text{I} \) in the MW, as measured by the Leiden–Argentina–Bonn (LAB, Kalberla et al. 2005) \( \text{H}_\text{I} \) survey (Fig. 1). The LAB survey has an angular resolution of \( 0.5 \times 0.5 \), but unfortunately our numerical simulation does not have enough particles to resolve structures on such small scales. We calculate the mean angular extent of the particles that contribute to the flux in a given direction on the sky in the simulated galaxy, and then smooth the LAB survey with a Gaussian kernel of the same width. At low galactic latitudes this smoothing angle is typically less than \( 1^\circ \). However, at high latitudes the mean smoothing length is much larger, and at \( |b| > 60^\circ \) can reach up to \( 20^\circ \) because of the relatively small number of SPH particles at these latitudes.

Both observed and simulated brightness maps display a bright and thin \( \text{H}_\text{I} \) disc in the plane of the MW, embedded in a thicker cooler envelope (\( T_B \sim 10^3 \) K), with an even cooler component (\( T_B \sim 100 \) K) at high velocities, \( |v_{lsr}| > 100 \text{ km s}^{-1} \), with respect to the local standard of rest (LSR). The brightness temperature \( T_B \), and its fall-off with latitude, is very similar in the observed and simulated maps. The minimum \( \text{H}_\text{I} \) brightness temperature in the simulated map is \( 95 \) K, in good agreement with \( \text{H}_\text{I} \) observations of the MW, where it is found that every line of sight contains easily observable \( \text{H}_\text{I} \). The simulated high-velocity gas (\( |v_{lsr}| > 100 \text{ km s}^{-1} \)) forms a nearly uniform background. Owing to the relatively small number of particles that are flagged as high-velocity at any one time the spatial resolution is poor, especially at high latitudes, and these simulations do not resolve the fine structure seen in the LAB survey. When the LAB data are smoothed to the same resolution as the simulation, the resulting distribution matches closely, with a mean brightness temperature of \( T_B \sim 23.22 \) K, as compared to \( 20.33 \) K in the simulations.

The velocity distribution of the simulated \( \text{H}_\text{I} \) also matches well with the LAB data (Fig. 2). Although we cannot resolve individual HVCs, the simulated \( \text{H}_\text{I} \) velocities are in good agreement with the properties of the HVC catalogue of Lockman et al. (2002). Lockman et al. identified some of the detections in this survey with external galaxies; we have removed these from the plot. Additionally, clouds that were identified as being part of the Magellanic stream, which dominate the extreme negative-velocity flow (Mathewson, Cleary & Murray 1974), were removed.

The line flux, \( \int S(\nu) \, d\nu \), for high-velocity gas, \( |v_{lsr}| > 100 \text{ km s}^{-1} \), is shown in Fig. 3. Solid black lines represent the results of Wakker (1991) with the emission due to the Magellanic stream and outer arm of the MW removed, as we do not expect an isolated galaxy to match these features. Errors on the mock data are calculated by repeating the measurements for observers at different points along the solar circle. The mock and real data look remarkably similar. The distribution of neutral gas perpendicular to the galactic plane is approximately exponential with a scale height of \( 5 \text{ kpc} \), in agreement with the predictions of Bregman (1980) for a galactic fountain. Although as noted in Fig. 3 the distribution of 21-cm emission in galactic latitude is slightly more concentrated in the simulated data.

Figure 1. All-sky maps of 21-cm brightness temperatures in the LAB survey (top panels) and in simulations (lower panels), integrated over all velocities (left-hand panels) or integrated over high velocities (\( |v_{lsr}| > 100 \text{ km s}^{-1} \)) only (right-hand panels). The observational data have been convolved with a spatially adaptive Gaussian, to make the angular resolutions of both the simulated and the observed data the same. Both observed and simulated galaxies consist of a thin \( (b < 5^\circ) \) \( \text{H}_\text{I} \) disc with brightness temperature \( T_B > 5000 \) K, embedded in a thicker \( (b > 45^\circ) \) disc with \( T_B \sim 1000 \) K, with \( T_B \sim 100 \) K at higher latitudes. The high-velocity gas has \( T_B \lesssim 100 \) K in both observed and simulated galaxies. The simulation does not reproduce the smaller scale structure seen in the LAB survey because of lack of numerical resolution.
Figure 2. Velocities with respect to the LSR of H I gas in the LAB survey (top panel) and the simulated galaxy (bottom panel) as a function of galactic longitude, $l$. Intensity on this plot is the 21-cm brightness of the H I, integrated over galactic latitude. The simulated galaxy has H I gas out to velocities of $|v_{\text{lsr}}| \sim 200$ km s$^{-1}$ in a characteristic pattern also seen in the LAB survey. The blue points (bottom panel) are HVCs from the catalogue of Lockman et al. (2002). The simulation does not resolve small clouds, but the velocity distribution of the simulated HI traces the same regions in ($l, v_{\text{lsr}}$) space as the observed clouds. The hatched region represents gas with $v_{\text{lsr}} < 90$ km s$^{-1}$

than in the observed data, when averaged over the whole sky the mean values of the smoothed maps agree to within 10 per cent, and are 485 K for the observed data and 446 K for the simulated data. It is difficult to measure the distances to HVCs in the real Universe. However, in our simulations this information is preserved and can be measured easily (Fig. 4). 50 per cent of the flux is emitted within a distance of 13 kpc from our observer. This figure is in line with that observed for other galaxies (Barbieri et al. 2005; Pisano et al. 2007), notably in M31 by Westmeier, Braun & Thilker (2005), who found that HVCs were generally at a projected distance of less than 15 kpc.

Gas in the fountain rains back on the disc at a radius ($r_{\text{returned}}$) which is generally larger than the radius ($r_{\text{ejected}}$) from where it was launched (Fig. 5). An SPH particle is classified as being part of the fountain if it is ejected to a vertical distance of more than 2 kpc from the galactic plane and at a later time falls back within 1 kpc of the galactic disc. The galactic fountain has an overall effect of moving gas from the inner part of the galactic disc to its outskirts: most fountain particles with $r_{\text{ejected}} < 8$ kpc have $r_{\text{returned}}/r_{\text{ejected}} > 4$, hence rain back outside the solar circle. Corbelli & Salpeter (1988) note that the effect of this ‘outer galactic fountain’ depends upon the physical properties of the gas that returns to the disc at large radii, and it could either evaporate the H I disc or cause it to grow. The rate at which gas returns to the outer disc in the simulations, $\dot{M} \sim 0.5 M_\odot$ yr$^{-1}$, is in agreement with observational estimates and could be enough to drive the observed turbulence (Santillán, Sánchez-Salcedo & Franco 2007). We find a peak mass flux of at least 0.5 $M_\odot$ yr$^{-1}$ through the disc out to a radius of 15 kpc, suggesting that a galactic fountain of this form is capable of driving ISM turbulence all the way to the outskirts of the galactic disc. In our simulations, $\dot{M}$ decreases gradually as the quiescent star formation
Neutral hydrogen in galactic fountains

Figure 5. Histogram showing the relation between the galactic radius at which gas is ejected from the galaxy \( r_{\text{ejected}} \) and the radius at which it next passes through the galactic disc \( r_{\text{returned}} \). Overall the galactic fountain acts to move gas from the centre of the galactic disc to its outskirts.

rate gradually decreases owing to the depletion of the local gas supply. However, we note that, in a fully cosmological setting, bursts of star formation due to galaxy mergers coupled with infall of gas from the surrounding intergalactic medium could continue to drive this process over the lifetime of the galaxy.

We conclude that our multi-phase star formation implementation naturally produces a galactic fountain in a MW-like model galaxy. The neutral hydrogen in the fountain has a spatial and velocity distribution in good agreement with a variety of observations for the MW and other spiral galaxies.

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