A link between feedback outflows and satellite galaxy suppression

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ABSTRACT
We suggest a direct, causal link between the two "missing" baryon problems of contemporary galaxy formation theory: (1) that large galaxies (such as the Milky Way) are known to contain too little gas and stars and (2) that too few dwarf satellite galaxies are observed around large galaxies compared with cosmological simulations. The former can be explained by invoking some energetic process – most likely AGN or star formation feedback – which expels to infinity a significant fraction of the gas initially present in the proto-galaxy, while the latter problem is usually explained by star formation feedback inside the dwarf or tidal and ram pressure stripping of the gas from the satellite galaxy by its parent. Here we point out that the host galaxy "missing" baryons, if indeed ejected at velocities of hundreds to a thousand km s$^{-1}$, must also affect smaller satellite galaxies by stripping or shocking the gas there. We estimate the fraction of gas removed from the satellites as a function of the satellite galaxy's properties, distance to the host and the strength of the feedback outflow. Applying these results to a Milky Way like dark matter halo, we find that this singular shock ram pressure stripping event may be quite efficient in removing the gas from the satellites provided that they are closer than $\sim 50-100$ kpc to the host. We also use the orbital and mass modelling data for eight Galactic dwarf spheroidal (dSph) satellites, and find that it is likely that many of them have been affected by the Galactic outflow, although the current data still leave much room for uncertainties. Finally, we point out that galactic outflows of the host may also trigger a starburst in the satellite galaxies by over-pressuring their gas discs. We speculate that this process may be responsible for the formation of the globular clusters observed in some of the Milky Way’s dSphs (e.g. the Fornax and Sagittarius dSphs) and may also be important for the formation of the bulk stellar populations in the dSphs.

1 INTRODUCTION
A potentially important problem for the current cosmological galaxy formation models was noted by Klypin et al. (1999) and Moore et al. (1999) in that the number of observed dwarf galaxy satellites is too small by a factor of at least ten compared with the simulations (for a recent review, see Bullock 2010). The suggested solutions to the problem are that dark matter halos of smaller mass are inefficient in acquiring their gas (Bullock et al. 2000) or turning that gas into stars, being more easily disrupted by star formation feedback (Dekel & Silk 1986). Alternatively, dwarf galaxies may be susceptible to influences from their host galaxies, e.g., due to tidal forces (Mayer et al. 2001) or by ram pressure stripping (Mayer et al. 2006). In the last decade, a number of ultra-faint galaxies were detected (e.g., Simon & Geha 2005), firmly suggesting for the first time that there is indeed a number of currently undetected almost baryon-free dwarf galaxies, supporting the idea that the astrophysical solutions listed above are responsible for modulating the numbers of satellite galaxies.

Interestingly, larger galaxies, including the Milky Way (McGaugh et al. 2009) also appear to lack about half of their baryons compared with the universal cosmological mass fraction of $\approx 0.16$ (Cen & Ostriker 1999). The missing gas does not seem to congregate in halos around the galaxies (Anderson & Bregman 2010), probably having been ejected by AGN and star formation feedback outflows well outside the galaxies (King 2003; Di Matteo et al. 2003). For a recent detailed census of the baryons in the local Universe see Shull et al. (2011).

The proposition that we make in this paper is that it is possible that the two missing baryon problems are in fact causally related. Mayer et al. (2006) show convincingly that ram pressure stripping, together with gravitational tides, is able to remove a significant fraction of gas from dwarf spheroidal galaxies (dSphs) orbiting the Milky Way. The ram pressure stripping is thus found to be important despite the low present day density of gas in the galactic halo (Anderson & Bregman 2010). Our key suggestion is that ram pressure stripping during the short but intense galactic outflow phases could be even more important because (a)
the density of the outflowing gas, $\rho$, could be much higher than that of the present day Galactic gaseous halo, and (b) the outflow velocity, $V_{sh}$, is also likely to be higher than the relative velocity between the satellite and the hot static halo. Since the ram pressure stripping is proportional to the ram pressure of the ambient gas, $P_{\text{ram}} = \rho V_{sh}^2$, the efficiency of this transient gas removal phase may be significant.

To demonstrate this point more clearly, we plot in Figure 1 the ram pressure seen by a satellite galaxy for three different models. The “Hot Halo” model (HH hereafter) follows Mayer et al. (2006), which assumes that the gas temperature is equal to the virial temperature of the Milky Way’s halo (modelled as an NFW potential, see Navarro et al. 1997); halo parameters are listed in §3 below, and the satellite’s orbital velocity is equal to twice the circular speed. This is approximately correct at the pericentre of an eccentric orbit, where Mayer et al. (2006) find that most mass is stripped off.

The two other “shock” models both mimic the physics of the AGN feedback theory by King (2003, 2005). This theory is based on observed fast ($v_{AGN} \sim 0.1c$) outflows from the nuclear (sub-parsec) regions of AGN (King & Pounds 2003). In the inner fraction of a kpc, these outflows are in the momentum-driven regime, which means that the fast outflow cools rapidly when shocked, and thus only its momentum is used to drive the gas out of the host galaxy. At larger radii that are of interest to us here, the fast outflow shock becomes non-radiative, and its energy is retained in the shocked primary outflow and in the kinetic energy of the shocked galaxy’s shell (Zubovas & King 2012). The outflow is then powered mainly by the kinetic energy of the fast wind, which is liberated at the rate $E_{AGN} \sim (v_{AGN}/2c)L_{Edd}$, where $L_{Edd}$ is the Eddington luminosity for the supermassive black hole launching the outflow.

In this model, in the spherically symmetric singular isothermal potential, the shocked shell outflow velocity, $V_{sh}$, is constant beyond $\sim$ a kpc distance from the SMBH, and is a few times the velocity dispersion of the singular isothermal sphere, $\sigma$ (see figures in King et al. 2011). This may appear paradoxical at first as the mass of the shocked gas increases as the AGN outflow sweeps through the galaxy. However, the energy and momentum of the nuclear AGN outflow increase linearly with time as well, so the ratio of the shocked mass to the fast AGN outflow mass actually stays constant, and this is why the velocity of the shocked shell is constant.

This analytical model can be only approximately correct for a more complicated non-spherically symmetric potential and gas distribution. It is clear that the outflow velocity is smaller in directions where the gas density is larger, e.g., along the galaxy midplane for a spiral galaxy (cf. the arguments of Zubovas et al. 2011; Zubovas & Navakshin 2012, for the Fermi Bubbles in the Milky Way). We do not consider this level of detail in our exploratory models here; we simply choose a constant outflow velocity in a spherically symmetric galaxy. Thus, in our model, the satellite ploughs through an outflow with velocity $V_{sh} = 500$ km s$^{-1}$. We make two different assumptions for $M_{sh}$, the mass of the outflowing shell. In the “NFW shell” model we assume that the mass of the outflowing gas is equal to 0.05 times the enclosed total mass of the halo at a given radius $R$. The mass of the outflow thus increases with radius in this model. The remaining “$M_{sh} = \text{const}$” model sets the outflowing mass to $M_{sh} = 5 \times 10^{10} M_\odot$, independent of radius $R$, which is 2.5 percent of the host galaxy mass within its virial radius (see section 3 for our Milky Way galaxy model). The first assumption is reasonable for a shell that is being continuously swept up and so its mass increases as it travels outward (King et al. 2011), whereas the second assumption is reasonable if a significant fraction of the gas within the virial radius first contracted to a high density central region e.g., the proto-bulge) and was subsequently ejected by the AGN and stellar feedback.

We see that the ram pressure in the two shock models is much larger than that in the present day hot halo model, which is mainly due to the fact that the present day’s Galactic gas halo is a low mass density one. The purpose of this paper is to investigate in greater detail the ram pressure stripping of smaller satellite galaxies by galactic outflows ultimately driven by SMBH and starburst feedback in the parent galaxy. To this end we first consider a toy model in which the galaxies are modelled as singular isothermal sphere (SIS) potentials. The advantage of this model is that it is purely analytical and easy to follow. We then consider a more realistic dark matter potential model for both the parent and the satellite, and assume that the dwarf galaxy contains both a gaseous disk and a gaseous halo. We consider separately the ram pressure effects on both these gas components. Finally, we apply the results to a sample of Milky Way dwarf galaxies.

### Figure 1

The ram pressure sampled by a satellite galaxy in the present day Galactic hot halo (lower curve), compared to the ram pressure in the Galactic outflow at velocity $V_{sh} = 500$ km s$^{-1}$, for two different assumptions about the mass in the outflow (see text for detail).

### 2 A TOY SPHERICAL SINGULAR ISOTHERMAL SPHERES MODEL

#### 2.1 Model galaxies

We start out by assuming that both the host and the dwarf satellite galaxies can be modelled by fixed singular isothermal sphere potentials with circular velocities $V_{\text{circ}} = 200 v_{200}$ km s$^{-1}$ and $v_{\text{circ}} = 20 v_{20}$ km s$^{-1}$, respectively. We assume...
that these potentials are dominated by dark matter, and that the gas makes up a small fraction of the total mass, so that the potential is approximately independent of the presence of gas.

We further assume (Mo et al. 1998) that the virial radius of the halo of the model galaxies is given by

$$R_{\text{vir}} = \frac{V_{\text{circ}}}{10H(z)},$$

(1)

where $H(z)$ is the Hubble constant at redshift $z$. The total mass within the halo is related to $V_{\text{circ}}$ as

$$M_{\text{tot}} = \frac{V_{\text{circ}}^2 R_{\text{vir}}}{G} = \frac{V_{\text{circ}}^3}{10GH(z)}.$$

(2)

Consider a satellite orbiting the host galaxy a distance $R$ from the centre of the host. The gas density profile inside the satellite is assumed to follow the dark matter with a constant fraction $f_3 < 1$ of the dark matter density. The gas surface density at radius $r$ from the centre of the satellite, projected along the direction from the centre of the host, is

$$\Sigma_{\text{g}}(r) = \frac{f_3 V_{\text{sh}}^2}{\pi G r}.$$

(3)

The gas in this model dwarf galaxy is acted upon by a massive rapidly moving shell of gas ejected from the parent galaxy, with the mass $M_{\text{sh}}$ and velocity $V_{\text{sh}} \gg V_{\text{circ}}$. The column density of the shell is

$$\Sigma_{\text{sh}} = \frac{M_{\text{sh}}}{4\pi R^2} = \frac{f_3 V_{\text{sh}}^2}{4\pi G R},$$

(4)

where $f_3 \ll 1$ describes the mass of the ejected shell with respect to the enclosed total mass at radius $R$ of the parent galaxy. The density of the shell is

$$\rho_{\text{sh}} = \frac{M_{\text{sh}}}{4\pi R^2 \Delta R},$$

(5)

where $\Delta R < R$ is the radial thickness of the incoming shell. The shell thickness is given by the difference between the forward shock velocity and that of the contact discontinuity, $V_{\text{cd}}$ (see Fig. 1 in Zubovas & King 2012). For the specific heat ratio of $\gamma = 5/3$ for the ambient shocked gas, those authors found that the result is $\Delta R = R/3$.

### 2.2 Shock ram pressure stripping

Following the standard (Gunn & Gott 1972), but at best approximate (see Mayer et al. 2006), treatment of ram pressure stripping, we assume that gas is ejected at radii where the restoring force per unit area, $\approx 2\pi G \Sigma_{\text{sh}} \Sigma_{\text{dg}}$, is smaller than the ram pressure of the shell’s material, $P_{\text{sh}} = \rho_{\text{sh}} V_{\text{sh}}^2$ (Gunn & Gott 1972). Here $\Sigma_{\text{dg}}$ is the total surface density of the dwarf galaxy (including the Dark Matter; the gas only surface density is named $\Sigma_{\text{g}}$). In this regime, the shock stripping radius, defined by

$$P_{\text{sh}} = 2\pi G \Sigma_{\text{sh}} (r_S) \Sigma_{\text{dg}} (r_S),$$

is equal to

$$r_S = \left( \frac{8f_3 V_{\text{sh}}^4 R^3}{3V_{\text{sh}}^2 G M_{\text{sh}}} \right)^{1/2},$$

(6)

where we assumed that $\Delta R = R/3$. Using the approximation $G M_{\text{sh}}/R = f_3 V_{\text{circ}}^2$, we have

$$r_S = \left( \frac{8f_3}{3f_3} \right)^{1/2} V_{\text{circ}}^2 R \approx 0.65 \text{ kpc} \left( \frac{f_3}{f_3} \right)^{1/2},$$

(8)

where $R_{100} = 500 R_{100}$ kpc and $V_{500} = V_{\text{sh}}/(500 \text{ km s}^{-1})$. The value of $r_S$ given by this equation is substantially smaller than the virial radius, $r_{\text{vir}}$, for the dwarf galaxy, indicating that most of the gas would be shock-stripped in this simple model, as we now show.

We can now calculate the fraction of the dwarf’s gas mass that is retained after the passage of the host’s feedback outflow, $\delta_{\text{ret}}$. Evidently, since the enclosed gas mass at radius $r$ is directly proportional to $r$ in our toy SIS potential model, $\delta_{\text{ret}} = r_S/r_{\text{vir}}$, where $r_{\text{vir}}$ is given by equation (7) with the circular velocity appropriate for the dwarf galaxy, and $r_S$ is calculated above. Based on equation (8) the result is:

$$\delta_{\text{ret}} = \sqrt{\frac{8f_3}{3f_3} \frac{V_{\text{circ}}^2}{V_{\text{sh}}} \frac{r}{R_{\text{vir}}}}.$$  

(9)

For $f_3 \sim f_3$, this predicts almost a complete loss of gas from the dwarf galaxy anywhere inside the host halo, e.g., $R < R_{\text{vir}}$.

It is instructive to compare this shock stripping mechanism with that due to gravitational tides within the halo of the galaxy host. Within the singular isothermal potential approximation for both the host and the satellite and the mass-radius scaling relations given by equations (4) and (5), the density of a galaxy at its effective radius is independent of the galaxy’s mass or circular velocity. Therefore the dwarf galaxy would also be tidally stripped in this model if it fell inside the host’s halo. Equation (9) is thus somewhat academic.

However, outside the host halo, the SIS model predicts no tidal destruction for the dwarf, whereas the shock stripping mechanism is still effective out to a radius several times $R_{200}$. This toy model is clearly very over-simplified compared with realistic galaxies, but it does indicate that the effect may be large, and calls for a more detailed investigation which we present below.

### 3 A MORE REALISTIC MODEL

We now build a slightly more realistic model for both the host and the dwarf galaxy by using the Navarro et al. (1997) potentials for the dark matter halos and the Mo et al. (1998) model for the disc of the dwarf galaxy. For definiteness, we set the host’s virial mass to $M_{\text{host}} = 2 \times 10^{12} M_{\odot}$, which gives a virial radius of $R_{\text{vir}} = 204$ kpc, and a circular velocity at the virial radius of $205 \text{ km s}^{-1}$. We set the concentration parameter to $c = 20$. This host galaxy model is compatible with the DM halo of the Milky Way (see e.g. Gnedin et al. 2010).

For the dwarf galaxy, we consider two plausible gas distributions within its dark matter halo: one distributed as the dark matter, with gas mass fraction $f_3 = 0.1$, and the other sitting in a rotation supported disc with the mass fraction of $f_3 = 0.05$. The disc surface density follows an exponential density profile (see Mo et al. 1998) with the scale-radius given by $r_d = 0.05 r_{\text{vir}}$, where $r_{\text{vir}}$ is the virial radius for the dwarf galaxy. We assume that the concentration parameter of the Navarro et al. (1997) halo, $c_{NFW}$, is $10$ for the dwarfs. This determines the potentials of the dark matter profiles...
and the disc in the dwarf galaxy completely; we neglect the contribution to the potential due to the disc of the host galaxy.

We should also specify the mass of the shell being expelled from the host, $M_{sh}$, which may be a function of the galactocentric radius, and the velocity of the shell, $v_{sh}$. To sample the range of possible outcomes we test two opposite assumptions for $M_{sh}$ as explained in the Introduction: (i) that the shell mass $M_{sh} = f_{sh}M_{enc}(R)$, where $f_{sh} = 0.05$ and $M_{enc}(R)$ is the total mass enclosed within radius $R$, and (ii) that $M_{sh} = 5 \times 10^{10} M_{\odot}$, independent of radius $R$.

Figure 2 shows the fraction of gas retained in the dwarf galaxy after the host feedback shock passage for the disc and the halo components, and also for the total gas mass, naturally defined as the sum of the halo and the disc masses. Three different total masses for the dwarf are considered, resulting in three different values for the maximum circular velocity in the galaxy, as marked in the top left corner of each panel. All the black curves in the figure are for the default shock velocity studied in this paper, $V_{sh} = 500$ km s$^{-1}$. We see that the halo gas component of the dwarf is the one easiest to remove as it is comparatively more extended than the exponential disc. The disc component is the most compact one, thus a ~90% removal of the disc requires the smallest dwarf (the top panel) to be at $R \lesssim 100$ kpc from the centre of the host. The figures show that the more massive the dwarf galaxy (i.e. the larger its $v_{\text{circ}}$) the harder it is to affect its gas by the shock from the host, since all the curves shift to smaller radii as we compare the top panel to the bottom one. Note that these trends are qualitatively consistent with the toy SIS model, cf. equation 9. The latter predicts that the radius at which a given fraction of gas is removed scales inversely with $v_{\text{circ}}$, which is approximately borne out in Figure 2. For example, the $\delta_{\text{ret}} \approx 0.1$ for the disc is reached at $R \approx 30$ kpc for the $v_{\text{circ}} = 60$ km s$^{-1}$ versus $R \approx 100$ kpc for the $v_{\text{circ}} = 15$ km s$^{-1}$.

To estimate the sensitivity of our models to the assumed value of $V_{sh}$, we also computed the fraction of gas retained in the halo of the satellite galaxy for two other values of $V_{sh}$, e.g., 300 and 1000 km s$^{-1}$ for the blue and the red curves, respectively, for the middle panel. We see that the gas is removed from the satellite more efficiently by a faster shock, as should be expected. Qualitatively, the dotted curve appears to shift to larger radii in roughly linear proportionality to $V_{sh}$. For example, the radius at which 90% of the halo is removed moves from $\sim 100$ kpc to $\sim 300$ kpc as $V_{sh}$ is changed from 300 to 1000 km s$^{-1}$.

Figure 3 shows the same calculation but now for the fixed mass of the expelled shell (case (ii) above). We observe that because of the $\sim 1/R^2$ ram pressure fall in this model, the transition from the strongly affected, e.g., $\delta_{\text{ret}} \ll 1$, to the weakly affected regime, $\delta_{\text{ret}} \sim 1$, occurs over a more restricted range of radii than in Figure 2. Furthermore, since the ram pressure in this model is lower (see Figure 1), the satellite galaxies need to be even closer to the centre of the host to be affected by the feedback shock.
Feedback outflows and satellite galaxies

Figure 3. Same as Figure 2 but for a fixed mass in the expelled shell of $M_{\text{sh}} = 5 \times 10^{10} M_\odot$. The meaning of the solid, dotted and dashed curves is the same as in Figure 2.

4 APPLICATION TO THE MILKY WAY DSPHS

We now compare the results of our simple calculations with the observed data for the dwarf spheroidal (dSph) satellites of the Milky Way. For more than a decade, a concerted observational effort has been underway to determine the dark matter content of the Milky Way dSph population (see Walker 2012, for a recent review) due to their importance for understanding galaxy formation on small scales. Although data are now available for more than twenty dSphs, in what follows we consider only the so-called “classical” dSphs, as these more luminous objects have constraints on both their dark matter content (Walker et al. 2009) and Galactocentric orbits (Lux et al. 2010).

Table 1 presents the data we have used in our comparison. The mass estimates at $r_{\text{half}}$ and $r_{\text{last}}$ are taken from Walker et al. (2007) who used Jeans equation modelling, combined with a Markov-Chain-Monte-Carlo (MCMC) algorithm, to determine masses for the dSphs based on their projected velocity dispersion profiles. We take the values for the orbital apo- and peri-centres to be those obtained by Lux et al. (2010) who applied an MCMC approach to the modelling of the space motions of the six dSphs which have been the subject of long-term proper motion studies.

Our comparison has two main steps to it: (i) first we build a NFW dark matter halo model and a corresponding gas disc model for each of the dSphs in Table 1 and (ii) we determine the ram pressure acting on the gas disc in the dSph and calculate how much of the gas remains in the disc after the shock’s passage. The results are summarised in Table 2.

To accomplish the first step, we calculate the circular velocity at $r = r_{\text{last}}$ for the dSph, and assume that it corresponds to the maximum circular velocity of a NFW halo hosting it. Since the dSphs’ circular velocity profiles are rather flat in the interesting range of radii in the dSph (e.g., see Fig. 1 in Mayer et al. 2006), this procedure does not appear to introduce large uncertainties. We then insert a gas disc with properties as described in §3, following the model of Mo et al. (1998). The gas mass of the model disc is given in column 3 of Table 2. This mass is the initial mass of the disc before the satellite is exposed to the influence of the ram pressure stripping.

For the second step, there is a range of possible models and further parameter choices to make. As our analytical study is clearly a rough approximation only, we calibrate its potential importance somewhat by applying the same analytical formalism to the ram pressure stripping by the present day “hot halo” (HH) model, which was shown to be effective for satellites on orbits with pericentres of $\sim 50$ kpc by the numerical simulations of Mayer et al. (2006).

Mayer et al. (2006) show that the gas stripping effect is strongly maximised near the pericentre of the satellite’s orbit, which is natural as both the hot halo density and the relative velocity of the galaxy and the gas reach their peak values at that point. Therefore, for the HH model, we repeat the procedure outlined in §2.2 for determining the radius $r_S$ outside of which the gas disc of the dSph is stripped, but using the model ram pressure appropriate for the Hot Halo. The mass of the gas retained in the dSph in this model is shown in the fourth column of Table 2.

Now, considering the effect of the galactic outflow on the satellite galaxies, it is most realistic to assume that these were near apocentres of their orbits at the time of the shock passage. This is because the objects spend most of the time there, and the shock passage is most likely to have found them at those more remote parts of their trajectories.

Table 1 shows that while the data on the dSphs have improved significantly over the last 5 years or so, the orbits of the satellites are still rather uncertain. In particular, the
for $r_a$ as (5) but for estimates are more model dependent than those of $M(\text{radius for the model dwarf galaxy}; (3) the initial mass of the gas disc, in units of $10^6$ Table 2. 

Table 1. Table of dSph structural parameters and results of mass modelling. The columns are: (1) dSph name; (2) observed V-band luminosity from (Irwin & Hatzidimitriou 1993); (3) projected half-light radius (the radius enclosing half of the total luminosity), as listed by Walker et al. 2009, assuming spherical symmetry and a King 1962 surface brightness profile with parameters taken from Mateo 1998; (4) Distance from Mateo 1998; (5) the radius of the outer bin in the velocity dispersion profile used in the mass modelling of Walker et al. 2009; (6) total mass inside $r_{\text{half}}$ Walker et al. 2009; (7) total mass inside $r_{\text{last}}$ Walker et al. 2009; (8) baryon fraction inside $r_{\text{last}}$; (9, 10) orbital pericentre and apocentre estimated by Lux et al. (2010) assuming the Milky Way halo model of Law et al. (2005). Note: In calculating the stellar masses from the measured luminosities, we assume that $M/L=1$ for the stellar components of the dSphs, and that the entire luminosity is contained within the radius $r_{\text{last}}$. The latter assumption is likely not valid for Sextans.

| Object      | $L_V / L_V^\odot$ | $r_{\text{half}}$ / pc | $d$ / kpc | $r_{\text{last}}$ / kpc | $M(r_{\text{half}}) / 10^5 M_\odot$ | $M(r_{\text{last}}) / 10^7 M_\odot$ | $f_b_{\text{last}}$ | $r_{\text{peri}}$ / kpc | $r_{\text{apo}}$ / kpc |
|-------------|-------------------|-------------------------|----------|--------------------------|--------------------------------------|------------------------------------|-------------------|------------------------|------------------------|
| Carina      | $(2.4 \pm 1.0) \times 10^3$ | 241.23                  | 101.5    | 0.87                     | $0.4^{+0.1}_{-0.1}$                   | $3.7^{+2.1}_{-1.8}$                 | 0.006             | 60 $\pm$ 30           | 110 $\pm$ 30           |
| Draco       | $(2.7 \pm 0.4) \times 10^3$ | 196.12                  | 82.6     | 0.92                     | $0.6^{+0.5}_{-0.3}$                   | $26.4^{+18.6}_{-17.4}$              | 0.001             | 90 $\pm$ 10           | 300 $\pm$ 100          |
| Fornax      | $(1.4 \pm 0.4) \times 10^3$ | 668.34                  | 138.8    | 1.7                      | $4.3^{+0.6}_{-0.7}$                   | $12.8^{+2.2}_{-1.5}$                | 0.13              | 120 $\pm$ 20          | 180 $\pm$ 50           |
| Leo I       | $(3.4 \pm 1.1) \times 10^3$ | 246.19                  | 250.30   | 0.93                     | $1.0^{+0.6}_{-0.4}$                   | $8.9^{+4.3}_{-5.2}$                 | 0.04              | –                      | –                      |
| Leo II      | $(5.9 \pm 1.8) \times 10^3$ | 151.17                  | 205.12   | 0.42                     | $0.5^{+0.2}_{-0.3}$                   | $1.7^{+1.9}_{-1.2}$                 | 0.03              | –                      | –                      |
| Sculptor    | $(1.4 \pm 0.6) \times 10^3$ | 682.117                 | 86.4     | 1.0                      | $1.6^{+0.4}_{-0.4}$                   | $2.0^{+1.0}_{-0.7}$                 | 0.02              | 70 $\pm$ 20           | 300 $\pm$ 200          |
| Sextans     | $(4.1 \pm 1.9) \times 10^3$ | 280.15                  | 66.3     | 0.74                     | $1.3^{+0.3}_{-0.5}$                   | $4.4^{+2.9}_{-2.0}$                 | 0.005             | 40 $\pm$ 20           | 90 $\pm$ 20            |
| Ursa Minor  | $(2.0 \pm 0.9) \times 10^3$ | 302.4                   | 52.9     | 1.3                      | $0.7^{+0.3}_{-0.3}$                   | $1.0^{+0.3}_{-0.3}$                 | 0.006             | 30 $\pm$ 10           | 100 $\pm$ 50           |

Table 2. Results of our ram pressure stripping modelling for the dSphs from Table 1. The columns are: (1) dSph name; (2) the disc scale radius for the model dwarf galaxy; (3) the initial mass of the gas disc, in units of $10^6 M_\odot$; (4) the mass of the gas retained in the HH model; (5) same for the NFW shock model with the dSph located at the estimated apocentre of the orbit, $a = a_0$ as in table 1; (6) same as (5) but for $a = a_0 + \delta a$; (7) same as (5) but for $a = a_0 - \delta a$; (8) the observed stellar mass in the dSph. Notes: The large estimate for $r_{\text{d}}$ in the case of Draco arises due to the large value of $M(r_{\text{last}})$ obtained by Walker et al. (2009). Those authors note that $M(r_{\text{last}})$ estimates are more model dependent than those of $M(r_{\text{half}})$ - it is therefore possible that the mass of the NFW model for Draco that we use here is over-estimated. However, it serves to illustrate the impact of an outflow on a dSph with a more massive halo.

| Object      | $r_{\text{d}}$ / kpc | $M_0$ / $10^6 M_\odot$ | HH | A | $A_{\text{max}}$ | $A_{\text{min}}$ | $M_{\text{obs}}$ / $10^6 M_\odot$ |
|-------------|----------------------|------------------------|----|---|------------------|------------------|----------------------------------|
| Carina      | 0.56                 | 16.6                   | 5.2 | 0.74 | 2.39             | 0.0016           | 0.24                             |
| Draco       | 1.47                 | 302.4                  | 248.3 | 251.0 | 268.4             | 212.9             | 0.27                             |
| Fornax      | 0.75                 | 40.3                   | 31.0 | 16.4 | 21.4             | 9.0               | 14.0                             |
| Leo I       | 0.84                 | 55.4                   | 52.4 | 34.1 | 42.6             | 13.7              | 3.4                              |
| Leo II      | 0.55                 | 15.6                   | 13.5 | 5.3  | 8.7              | 0.32              | 0.59                             |
| Sculptor    | 0.82                 | 52.9                   | 25.0 | 20.1 | 31.0             | 2.37              | 1.4                              |
| Sextans     | 0.39                 | 5.5                    | 13.2 | 2.3  | 3.69             | $2.5 \times 10^{-3}$ | 0.41                             |
| Ursa Minor  | 0.66                 | 27.7                   | 4.5  | 0.79 | 2.64             | 0.005             | 0.2                              |

apocentres for many dSphs are uncertain by a large factor, and are not known at all for Leo I and Leo II. To take these uncertainties into account to some degree, we merely use the nominal, the minimum and the maximum values of the apocentres from Table 1. That is, denoting the apocentre values from Table 1 as $a_0 \pm \delta a$ for each dSph, we calculate its disc disruption by the shock for the three values of $a = a_0$, $a = a_0 + \delta a$ and $a = a_0 - \delta a$, respectively, and list them in columns marked by “A”, “$A_{\text{max}}$” and “$A_{\text{min}}$”. For Leo I and II we assumed, somewhat arbitrarily, that their apocentres are equal to their current galactocentric distance, e.g., $a_0 = d$, and that the error in their apocentres is half that ($\delta a = d/2$).

Comparison of the “HH” and the “A” models from Table 2 demonstrates that for most dSphs the shock ram pressure stripping is roughly as important as the hot halo ram pressure stripping, although some dSphs are dominated by one effect or the other. This is somewhat counter-intuitive given the much higher ram pressure of the shock outflow (Figure 1), but can be reconciled with the expectations by noting that the satellites may be much further from the host in the model A than they are in the model HH.

Further, the next two columns in Table 2 show that the present orbital data on dSphs are still not sufficiently accurate to make a firm decision on whether the feedback outflow stripping of the observed dSphs is important or not. Indeed, column 6 (labeled “$A_{\text{max}}$”) shows that by placing the dSphs at the maximum distance consistent with the data,
the effect of the shock passage is minimised to the point that only Carina and Ursa Minor are strongly affected. On the other hand, if the satellites are placed at the minimum allowed distance (column 7 labeled “\( A_{\text{min}} \))
, the gas stripping is strongly enhanced; only Draco remains largely unaffected.

In conclusion, there is clearly scope for the observed dSphs to have suffered major disruption due to outflows from the Milky Way. However, better orbital data and internal models for the dSphs are needed to investigate this further.

5 Induced Star Formation in the dSphs

There is another potentially significant way in which galactic outflows could influence the observed properties of the Milky Way dSphs.

Massive stars are observed (Deharveng et al. 2005) to produce not only negative but also positive feedback on their immediate gaseous environment. Shocks driven by supernova explosions, stellar winds or photo-ionisation can pressurise the surrounding ambient gas to high densities and result in star formation. Galactic outflows are very likely to result in triggered star formation as long as the shocked ambient gas is able to cool rapidly (Nayakshin & Zubovas 2012, submitted).

We shall now show that the host galaxy outflow is capable of inducing star formation in the dSphs. The mid-plane density in the gas disc of the dSph is of the order of \( \Sigma_g \), where \( h \) is the vertical scale height of the gas disc, and \( \Sigma_g \) is the gas only surface density of the dSph. Therefore, the disc pressure is

\[
P_{\text{disc}} \approx \frac{\Sigma_g v_s^2}{h},
\]

(10)

where \( v_s \) is the sound speed in the disc. For a gas disc in hydrostatic balance, \( c_s/v_{\text{circ}} = h/r \) (Shakura & Sunyaev 1973). Further, we approximate \( M_{\text{disc}}(r) \approx \Sigma_g(r) \pi r^2 \), where \( M_{\text{disc}}(r) \) is the total enclosed mass within \( r \) for the dSph, and \( \Sigma_g(r) \) is the total surface density at that radius. Noting that \( v_{\text{circ}}^2 = GM_{\text{disc}}/r = \pi Gr\Sigma_g(r) \), we estimate the mid-plane pressure in the gas disc as

\[
P_{\text{disc}} \approx \frac{\Sigma_g v_s^2}{h v_{\text{circ}}^2} v_{\text{circ}}^2 \approx 2\pi G \Sigma_g(\Sigma_g h/2r).
\]

(11)

Regions where the disc pressure is smaller than the ram pressure of the outflow, i.e., where

\[
P_{\text{out}} > P_{\text{disc}} = 2\pi G \Sigma_g(\Sigma_g h/2r),
\]

are susceptible to compression and triggered star formation. Comparing this condition with a similar condition for removal of the gas from the dSph (disc truncation) given by equation 6, we see that the zone where the host’s outflow can induce star formation in the satellite is larger. Indeed, since \( h/r < 1 \), there is a region of the disc inward from the shock truncation radius, \( r_S \), where \( P_{\text{disc}} < P_{\text{out}} < 2\pi G \Sigma_g \Sigma_g h/2r \), so that the gas in the disc of the dSph is compressed but not expelled. At radii \( r > r_S \) the gas is both expelled and compressed to higher densities.

This implies that the host’s galactic outflow can also trigger a local starburst in the dSph satellite. Furthermore, there may be several mass ejection episodes for the host galaxy, e.g., one during the birth of the protogalaxy, and then more during major merger(s) powerful enough to trigger either a quasar-driven outflow or a significant starburst in the host. As the dSph presumably contains less and less gas as time progresses, it becomes progressively easier to induce a starburst in it in each subsequent episode of the host galaxy outflow (Eq. 11). It is also worth noting that the inner edge of the region in which star formation can be triggered moves inwards as the gas mass in the dwarf decreases. Combined with the pollution of the remaining gas by previous bursts of star formation this could provide a natural explanation of the radial metallicity gradients observed in many dSphs, in which more metal rich, and younger, populations are more centrally concentrated (see e.g. de Boer et al. 2012a,b). On the other hand, shock gas stripping alone produces a metallicity gradient, since stars in the outer regions of the dwarf galaxy may form only early on, before the gas was expelled from those regions; the inner regions of the satellite can continue star formation since they retain their gas.

Nayakshin & McLaughlin (2013, submitted) argue that galaxy outflows produce enormous pressures. In the case of quasar-driven outflows the pressure exceeds average pressure in the host galaxy gas by a factor as large as a few tens. They suggested that the result of this high ambient gas pressure is the formation of very compact star clusters by over-pressurising Giant Molecular Clouds (GMC). The sizes of the resulting clusters are comparable to that of the Globular Clusters. Similarly, we suggest that over-pressurising of the gas in the dwarf galaxy caused by the passage of the host galaxy’s outflow may initiate formation of Globular Clusters in dwarf galaxies. Recently, Assmann et al. (2013) proposed that dwarf galaxies could have formed from the merger of star clusters in low-mass dark matter haloes. The passage of an outflow would provide a natural way to trigger the clustered star formation which is the basis of those models.

It is also possible that the material ejected from the dwarf, e.g., gas at \( r > r_S \), clumps up to form stars, as long as it is able to cool rapidly enough. This may create a population of globular clusters at large galactocentric radii whose gas originated from dwarf satellites of the host.

There is a testable prediction that this picture makes which we hope could be checked observationally in future. Namely, starbursts in satellite galaxies induced by an outflow from a much larger host galaxy are co-eval within the time required for the outflow to sweep the host galaxy (e.g., tens to \( \sim 100 \) Million years), a time that is very short compared with the age of the host and the satellites. Assuming that the starbursts produce observationally significant amount of stars and/or globular clusters per dwarf this suggests that there should be co-eval peaks in the star formation history of seemingly unrelated dwarf galaxies. Current data are consistent with all dSphs having had an early burst of star formation more than 10 Gyr ago (e.g. Tolstoy et al. 2004), although the uncertainties associated with the ages of stellar populations make it difficult to establish whether these bursts were exactly co-eval. The range of star formation histories exhibited by the dSphs in their subsequent evolution (e.g. de Boer et al. 2012a,b) may indicate that a hybrid model involving both AGN-driven shocks and inter-
action with the hot halo are required to understand fully the Milky Way’s dSph population.

6 DISCUSSION AND CONCLUSIONS

We have noted that the ram pressure of galactic outflows driven by either quasars/AGNs or powerful starbursts in a host galaxy is large enough to affect the gas in the satellite dwarf galaxies orbiting the host. We first demonstrated the point for a simple, singular isothermal sphere model for the host and the satellite galaxies (32), and we then considered a more realistic Navarro et al. (1997) potential. Considering separately the gas settled in a rotationally supported disc, and also a gaseous hot halo of the dwarf galaxy, we calculated the fraction of gas ejected from the satellite by the host’s outflow and the fraction of gas retained (see Figs. 2 and 3 in 31). As an example, we found (see fig. 2) that for a Milky Way like host, a small dwarf (with maximum circular velocity $v_{\text{circ}} = 15$ km s$^{-1}$) loses practically all its gas if it is within $\sim 100$ kpc of the centre of the host galaxy. The same occurs for distances closer than $\sim 30$ kpc for a much more massive satellite with $v_{\text{circ}} = 60$ km s$^{-1}$. In 31 we considered a well defined sample of dSph galaxies of the Milky Way, using the latest available data for their orbits in the Galactic halo and assuming NFW models for the dSphs’ internal structure. We found that many, if not most, of the dSphs in the sample could well have been affected by the putative Galactic outflow; unfortunately, the orbital data in particular are still not accurate enough, which leaves significant room for uncertainty for most of the dSphs.

We now compare the overall energetics of our outflow stripping the Galaxy of most of its gaseous mass out to its virial radius with the likely feedback energy sources: the SMBH named Sgr A* and the stellar population of the Galaxy. The total amount of kinetic energy in the most energetic model we studied here – the NFW shock – is

$$E_{\text{sh}} = M_{\text{sh}} \frac{V_{\text{sh}}^2}{2} \approx 10^{16} M_\odot (\text{km/s})^2,$$

(13)

where $M_{\text{sh}} \approx 10^{11} M_\odot$ is the total mass of the shell driven outward to the virial radius of the Galaxy. This estimate is made for $V_{\text{sh}} = 500$ km s$^{-1}$. Now, for Sgr A*, the black hole mass is $M_{\text{BH}} = 4.4 \times 10^6 M_\odot$ Genzel et al. (2010). The total kinetic energy released in the fast outflow in King (2003) model is

$$E_{\text{BH}} = \frac{1}{2} \frac{v_{\text{AGN}}^2}{c} \epsilon M_{\text{BH}} c^2 \approx 2 \times 10^{15} M_\odot (\text{km/s})^2,$$

(14)

where $\epsilon \approx 0.1$ is the standard radiative efficiency for disc accretion Shakura & Sunyaev (1973) and $v_{\text{AGN}} \sim 0.1c$ is the fast nuclear outflow velocity King & Pounds (2003).

We observe that $E_{\text{BH}}$ is a factor of $\sim 5$ below the required energy, $E_{\text{sh}}$. However, if the outflow was somewhat focused along the direction perpendicular to the Galactic plane then the energy requirement could be met along those directions. Only the satellites located in those directions would then be affected by the ram pressure shock discussed here. In addition, it is certainly possible that $\epsilon \sim 0.2$ if the SMBH is rotating rather than not, and $v_{\text{AGN}}$ could be somewhat larger. We could also have over-estimated the mass of the gas in the shell escaping the Galaxy. Therefore we believe that while Sgr A* fails to power the most energetic shell of the two considered here with the default parameters, there is still plenty of parameter space where feedback from Sgr A* could be sufficient for a significant impact on the Galaxy’s satellites.

For stellar feedback, we consider only supernovae type II, for which the Kroupa (2002) IMF yields the kinetic energy output of $\sim 5 \times 10^8 M_\odot (\text{km/s})^2$ per $1 M_\odot$ of the total stellar mass in the population (this is derived assuming that each SNe releases $10^{51}$ erg of kinetic power, and that all stars more massive than $8 M_\odot$ yield type II SNe. Now, the total stellar mass of the Milky Way is estimated at $M_{\text{tot}} \sim 6 \times 10^{10} M_\odot$ McMillan (2011), which releases a total of $3 \times 10^{16} M_\odot (\text{km/s})^2$ in SN type II over the lifetime of the Galaxy. If a significant fraction, e.g., $\sim 1/3$, of this energy were released in the star burst, then this would be sufficient to power our most energetic outflow.

Finally, recent detailed AGN feedback simulations Nayakshin & Zubovas (2013) and analytical models (Zubovas et al. 2013, MNRAS submitted) show that AGN outflow may actually trigger (at least accelerate) a very powerful star burst in a gas-rich phase of galaxy formation. In that scenario both the SMBH outflow and the starburst SN type II would pump the energy into the outflow clearing the galaxy of gas. We therefore conclude that our model does not require an unreasonable amount of energy.

The shock ram pressure stripping process considered here is yet another plausible way to resolve the “missing satellite” problem of the Milky Way, which we note could have operated in conjunction with the tidal stripping and the ram pressure stripping of the satellite galaxies due to the present day hot halo of the Galaxy. Having a dwarf galaxy harassed by the Galactic outflow early on does not preclude its further harassment by the present day hot halo e.g., Mayer et al. (2006), and in fact should increase the efficiency of the latter process: a less massive gas disc is easier to strip away from the dwarf by the hot halo’s ram pressure.

We also pointed out (31) that the pressure in the host galaxy’s outflow is sufficient to compress the gas in the discs of the dwarf galaxies and thus trigger star formation there. Observationally this picture could be tested by looking for a co-evol spike in the star formation histories of the dwarfs of the Milky Way. Additionally, the epoch of Galactic outflow may be the best time to form Globular Clusters – not only in the main Galaxy but also in the dwarf satellites, as the outflow provides both very high ram and external pressures (cf. Nayakshin and McLaughlin, 2013).

Finally, we note that we have not considered the possible collimating effect on the outflow of the presence of a massive disk in the host galaxy. In this case, the impact on the satellite population might not be isotropic, giving rise to anisotropies in the distribution of detectable satellites around the host, or variations of satellite properties depending on their locations relative to the outflow direction. Such structures need not necessarily be aligned with the plane of the present-day disk, as the outflow is generated during a major merger whose angular momentum could lead to an accretion disk around the central SMBH which was randomly oriented relative to the larger-scale galactic disk. This effect might explain the presence of large-scale, flattened structures in the distribution of satellite galaxies around both the Milky Way (Pawlowski et al. 2012) and M31 (Ibata et al. 2013) which have been claimed in the literature. Further ex-
ploration of our model is required to determine its impact on the spatial distribution of satellites around a host.

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