Quasar outflows and the formation of dwarf galaxies

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ABSTRACT
In this paper we propose a scenario for the formation of a population of baryon-rich, dark-matter-deficient dwarf galaxies at high redshift from the mass swept out in the intergalactic medium (IGM) by energetic outflows from luminous quasars. We predict the intrinsic properties of these galaxies, and examine the prospects for their observational detection in the optical, X-ray and radio wavebands. Detectable thermal Sunyaev–Zel’dovich decrements on arcminute scales in the cosmic microwave background radiation maps are expected during the shock-heated expanding phase from these hot bubbles. We conclude that the optimal detection strategy for these dwarfs is via narrow-band Lyman-α imaging of regions around high-redshift quasars. A scaled-down (in the energetics) version of the same model is speculated upon as a possible mechanism for forming pre-galactic globular clusters.

Key words: globular clusters: general – galaxies: formation – intergalactic medium – quasars: general – cosmic microwave background – dark matter.

1 INTRODUCTION
Galaxy formation is a complex physical process involving several length-, mass- and time-scales, and so it is expected to proceed in a fashion that is modulated by the properties of the local environment in which it occurs. In the context of a hierarchical picture for structure formation in a cold-dark-matter-dominated universe, most in which it occurs. In the context of a hierarchical picture for structure formation in a cold-dark-matter-dominated universe, most massive galaxies are though to assemble fairly recently (at z ~ 0.5–1) from the agglomeration of subclumps that have collapsed at higher redshifts (White & Frenk 1991; Kauffmann, White & Guiderdoni 1993; Baugh, Cole & Frenk 1996). Recent observations from the Hubble Space Telescope (HST) and ground-based telescopes indicate that a significant fraction of the stellar mass, as traced by blue light, that constitute galaxies is in place by redshift ~1.5–2.0 (Lilly et al. 1996; Madau 1998). The other cosmological objects in place by these redshifts are quasars and, given the high bolometric luminosities of high-redshift quasars, it is natural to expect that they probably play an important role in locally modulating galaxy formation (Efstathiou & Rees 1988; Babul & White 1991; Babul & Rees 1992; Silk & Rees 1998).

We propose that quasars affect galaxy formation in their vicinity via energetic outflows. The outflow powered by the mechanical luminosity of the quasar shocks and sweeps out mass from the intergalactic medium (IGM) into a (thin) shell that propagates out on scales of the order of a few hundred kpc. The swept-up matter expands adiabatically until a gravitational instability of the shell causes it to fragment, yielding clumps with a typical mass-scale ~10^5 M_☉, corresponding to the mass of dwarf-galaxy-size objects, akin to the explosion-driven galaxy formation scenarios proposed by McKee & Ostriker (1977), Ostriker & Cowie (1981) and Ostriker & Ikeuchi (1983). The propagation of these cosmological blastwaves has been computed by Ostriker & Cowie (1981), Bertshinger (1985), Carr & Ikeuchi (1985), Vishniac, Ostriker & Bertshinger (1985) and Tegmark, Silk & Evrard (1993) in slightly different contexts, that of explosion-induced structure formation models or the role of supernova winds. In recent papers Voit (1996) has examined the effects of quasar-blown bubbles on the structure of the IGM; here we focus on the fate of the gas in these bubbles. We consider the basic scaling relations for our proposed model in Section 2. In Section 3 we outline the dynamics of quasar outflows and the fate of the cold dense gas deposited in shells around the quasar, when gravitational instability causes mass clumps to form at the scale of dwarf galaxies. In Section 4 the predicted properties and prospects for detection of this population dwarfs and the outflow in the optical and X-ray wavebands are explored. We then note that the high-redshift blue clumps detected by the HST and reported by Pascarelle et al. (1996) and the galaxies detected in Lyman α (Lyα) by Hu & McMahon (1996) are potential candidates (Section 5). Before concluding, we speculate on the consequences of a scaled-down version of the same scenario for the formation of the pre-galactic globular cluster population.

2 QUASAR OUTFLOWS
The total energy budget available from a quasar to power the mechanical luminosity of the outflow is determined by the mass accreted by a black hole (BH) of mass M_\text{BH} modulo two efficiency factors: one that determines the conversion of rest mass into the
bolometric luminosity $\epsilon$ ($\sim 0.1$), and the efficiency of conversion of the bolometric luminosity into mechanical luminosity parametrized as $\epsilon_L$ ($\sim 0.5$). Bolometric luminosities of bright quasars at redshifts $z \gtrsim 2$ are as high as $\sim 10^{47}$ erg s$^{-1}$ or larger. A typical outflow can therefore sweep up mass $M_{\text{IGM}}$ from the IGM:

$$M_{\text{IGM}} \sim 2 \times 10^{12} \frac{L_{\text{QSO}}}{10^{47} \text{ erg s}^{-1}} \left( \frac{\delta t}{5 \times 10^7 \text{ yr}} \right) \frac{v_{\text{flow}}}{3000 \text{ km s}^{-1}}^2 M_\odot,$$

(1)

where $\delta t$ is the duration of the wind phase/the lifetime of the quasar, $v_{\text{flow}}$ is the outflow velocity, and $L_{\text{QSO}}$ is the mechanical luminosity of the quasar. The outflow extends to

$$R \sim 500 \left( \frac{\epsilon_L}{0.05} \right)^{1/3} \left( \frac{M_{\text{bh}}}{10^9 M_\odot} \right)^{1/3} \left( \frac{f_Q}{0.01} \right)^{-1/3} \frac{v_{\text{flow}}}{0.1} \sqrt{c} \text{ kpc},$$

(2)

where $f_Q$ is the local baryon fraction in units of 0.01. Note that if the density of the ambient medium is lower, then the outflow expands further out on to larger scales. All the numbers quoted in this work have been computed for $H_0 = 50$ km s$^{-1}$ Mpc, $\Omega_0 = 1.0$ and $\Lambda = 0$.

3 OUTFLOW DYNAMICS

Below, we summarize the dynamical sequence before estimating the relevant numbers. In this treatment we ignore the detailed microphysics of the outflow from the BH, but assume that the flow is a mildly relativistic and directed one involving only a small mass at the base of the outflow. We also ignore the time evolution of the initial stages of the outflow, and consider the dynamics of the outflow only at the epoch when the swept-up mass is comparable to or greater than the mass of the BH, $M_{\text{bh}}$.

During the lifetime of the quasar ($t_{\text{QSO}} \sim 5 \times 10^7$ yr), the outflow expands freely into the IGM, shock-heating material locally to high temperatures $\sim 10^6$ K. During the hot phase, we expect X-ray emission from the shocked material. For quasars that switch on at high redshifts ($z > 7$) inverse Compton heating will dominate, but at low redshifts the shocks expand adiabatically and cool radiatively. As the mass accumulated around the shock becomes dynamically significant, a reverse shock propagates, thermalizing the gas that is concentrated along a thin shell. This shell subsequently evolves adiabatically, akin to supernova remnants until the age of the bubble becomes comparable to the total elapsed Hubble time at that redshift, at which juncture cosmological effects alter the structure of the outflow and its growth.

Outflows originating after $z \sim 7$, with energies greater than $10^{47}$ erg remain adiabatic to low redshifts (Bertschinger 1985). The assumption of adiabatic expansion remains valid [the post-shock density being roughly 4 times the density of the ambient IGM, and the radius $R(t)$ of the bubble scaling at $t^{2/5}$ once the QSO shuts off] until the shell of mass swept up at the shock front becomes self-gravitating. In this treatment we focus on the dynamics of the outflows during this radiative-cooling-dominated stage. They are well approximated by the family of self-similar Sedov–Taylor blast-wave solutions (McKee & Ostriker 1977; Bertschinger 1985; Voit 1994, 1996) at this epoch. The swept-up mass becomes dynamically important at a time $t$ after the commencement of the outflow:

$$t \sim 5 \times 10^7 (1 + z)^{-3/2} \Omega_{\text{IGM}}^{-1/2} \left( \frac{M}{4 \times 10^4 M_\odot \text{ yr}^{-1}} \right)^{1/2} \times \left( \frac{v_{\text{flow}}}{3000 \text{ km s}^{-1}} \right)^{-1/2} \text{ yr},$$

(3)

where $M$ is the mean outflow rate (i.e., $M_{\text{IGM}}/t_{\text{QSO}}$) in units of $4 \times 10^4 M_\odot$ yr$^{-1}$, and $\Omega_{\text{IGM}}$ is the mass density of the IGM (where $\Omega_{\text{IGM}} \ll \Omega_0$, at which time the bubble radius is

$$R \sim 400 (1 + z)^{-3/2} \Omega_{\text{IGM}}^{-1/2} \left( \frac{M}{4 \times 10^4 M_\odot \text{ yr}^{-1}} \right)^{1/2} \times \left( \frac{v_{\text{flow}}}{3000 \text{ km s}^{-1}} \right)^{-1/2} \text{ kpc}.$$  

(4)

Eventually, as the age of the bubble approaches the local Hubble time, the cold shell of accumulated material fragments due to gravitational instability (although in principle, while Rayleigh–Taylor instabilities could set in, they do not result in the formation of gravitationally bound fragments). The boundary conditions immediately prior to fragmentation can be estimated, following the treatment of Ostriker & Cowie (1981) and Voit (1994). The radiative cooling time $\tau_{\text{cool}}$ is

$$\tau_{\text{cool}} = 1.2 \times 10^8 \left( \frac{T}{10^6 \text{ K}} \right)^{1/5} (1 + z)^{-3} \text{ yr}.$$  

(5)

Equating the radiative cooling time to the age of the bubble, an expression for the post-shock velocity $v_{\text{cool}}$ can be obtained (Ostriker & Cowie 1981) in terms of the total energy injected into the outflow,

$$v_{\text{cool}} \sim 150 \left( \frac{L_{\text{QSO}}}{10^{47} \text{ erg s}^{-1}} \right)^{1/20} \left( \frac{\delta t}{5 \times 10^7 \text{ yr}} \right)^{1/20} (1 + z)^{1/3} \text{ km s}^{-1}.$$  

(6)

The shell temperature can be related to the total swept-up mass as follows:

$$T_{\text{shell}} = 1.4 \times 10^5 \left( \frac{M_{\text{swep}}}{10^{12} M_\odot} \right)^{2/5} (1 + z)^{3/5} \text{ K}.$$  

(7)

The maximum mass that can cool during the radiative cooling phase is $10^{12} M_\odot$, and fragments less than $10^9 M_\odot$ are not Jeans-unstable at this epoch, thereby naturally providing typical mass-scales. Fragmentation on a scale $\xi$ can therefore occur if a small disc of radius $\xi$ and mass $M_{\text{swep}}^{-1/2}\xi^2/R^2$ extracted from the shell has a gravitational collapse time that is less than the sound-crossing time along $2\xi$. The instability therefore imprint a characteristic mass-scale,

$$M_{\text{frag}} \sim 5 \times 10^7 \left( \frac{E}{10^{47} \text{ erg}} \right)^{-3/10} (1 + z)^{3/2} M_\odot,$$

(8)

which is roughly $10^{9–10} M_\odot$ (McKee & Ostriker 1977; Ostriker & Cowie 1981) for the numbers in equations (1) and (2), leading to the formation of a group of dwarf galaxies around the quasar from the total swept-up mass. While these clumps are not generally bound to each other, they are highly clustered both spatially and in velocity space. Note here that lower energy outflows imply a high fragment mass, although a smaller value of the gas mass is swept up initially; therefore weaker outflows from lower luminosity QSOs or super-winds (Heckman, Armus & Miley 1987; Barthel & Miley 1988) could be important for the formation of dark-matter-poor galaxies at lower redshifts.

The outflow material can suffer one of three fates: it may stall and.
fall back, if the mass swept up is large and the central potential well is deep (e.g., if the quasar is at the centre of a protocluster); the outflow may coast to infinity (in practice, until it matches on to the Hubble flow); or it may escape the central object hosting the quasar but be bound to the protocluster, yet not fall back to the centre on radial orbits if the protocluster potential is strongly non-spherical. The condition for fall-back can be estimated using a density profile \( \rho(r) \) to describe the dark matter profile around the quasar. The fragments coast on only if \( v_{\text{flow}} \) exceeds the local escape velocity \( v_{\text{esc}} \) of the total potential at a given distance \( r \) from the nucleus:

\[
v_{\text{esc}} \sim 300 \left( \frac{M(r)}{10^{15} M_\odot} \right)^{1/2} \left( \frac{r}{1 \text{ Mpc}} \right)^{-1/2} \text{ km s}^{-1}.
\]

3.1 Traditional scenarios for the formation of dwarfs

Dwarf galaxies can form directly from the collapse of cosmological density fluctuations at high redshift (Ikeuchi & Norman 1987), in which case we expect them to be dark-matter-dominated, especially since the first generation of star formation may unbind most of the gas in the disc (Dekel & Silk 1986), unless the disc formed from a high-angular-momentum perturbation and has low surface density with sparse star formation, in which case we would see the high-z counterpart of a gas-rich object with a dark-matter-dominated rotation curve at low \( z \) (deBlok, McGaugh & van der Hulst 1996).

Babul & Rees (1993), however, have argued that the cosmological collapse of dwarf galaxy scale masses is inhibited until \( z \approx 1 \) due to the photoionization of the IGM by the metagalactic UV radiation. Therefore their model and subsequent work by Babul & Ferguson (1996) predict a formation scenario for low-mass galaxies at recent epochs that fade after a burst of star formation at \( 0.5 \leq z \leq 1 \). These resultant low-luminosity, low-surface-brightness objects are claimed to dominate the blue number counts at faint magnitudes in redshift surveys (Ellis 1997), but cannot be reconciled with the red counts (cf. Bouwens & Silk 1996).

Interactions of large, gas-rich spirals may also lead to the formation of gas-rich, dark-matter-poor dwarf galaxies by the fragmentation of extended or unbound tidal tails (Dubinski, Mihos & Hernquist 1996). Such dwarfs would form in small numbers near major mergers and are likely to fade rapidly after the initial burst of star formation, and would therefore be seen only in the close vicinity of recently merged spirals.

The population of dwarf galaxies postulated here is distinguished by forming predominantly at high redshift, in large groups spread in an approximate sheet geometry over \( \sim \text{Mpc} \) scales. These dark-matter-deficient objects are characterized by low-amplitude rotation curves and low central velocity dispersions. Since they form from the fragmentation of a thin shell, the clumps have low specific angular momentum and are hence likely to collapse into relatively compact structures, with a brief star-forming phase until supernovae remove or disperse the bulk of the remaining gas (Couchman & Rees 1986; Dekel & Silk 1986). These dwarfs would form in small numbers (\( \sim 1 \) per \( L_\odot \) galaxy) at high \( z \) only, but may be observationally of interest due to their strong clustering and association with nearby bright quasars.

4 PREDICTED PROPERTIES OF THE POPULATION

The dwarf galaxies that form on the cooling of these fragments are expected to have the following properties.

1. They are baryon-rich and dark-matter-deficient, so the typical rotation curve will have a much lower amplitude than, say, that for a local dwarf with a comparable luminous mass; hence these dwarf galaxies are expected to have disc-dominated rotation curves.
2. Since the swept-up material is principally from the IGM at high redshift, that is not very enriched, they are expected to be metal-poor, with \( [Z] \sim 10^{-2} Z_\odot \).
3. Since the dwarfs do not contain significant amounts of dark matter, we expect that the first few supernovae (SNe) can entirely disrupt the remaining gas disc, truncating star formation, and therefore the surface number density of these galaxies per square degree is likely to decline rapidly at lower redshifts, as the galaxies fade after the initial burst of star formation.
4. The dwarfs are expected to be highly clustered, as they form in a sheet around the quasar. Therefore any line of sight to a background quasar through a group of nascent dwarfs may intersect many individual members with narrow velocity spacing, producing a characteristic signature in the absorption-line profiles. Each absorption line would also be relatively narrow compared to lines of the same column density at low redshifts, as the internal velocity dispersion of these dark-matter-deficient galaxies is lower, and as the associated gravitational potentials are fairly shallow, while their baryonic fraction is extremely high.
5. The gas that settles down into the disc in these systems is likely to form compact, subcritical discs (sub-\( L_\odot \)) and hence star formation is likely to ensue in intense bursts in isolated knots.
6. Since the dwarfs form from gas clumps with low specific angular momentum, the gas can be funnelled in to the centre very efficiently to form a compact central object. Therefore these dwarfs are likely to harbour weak AGN, with narrow emission lines \( \sim M_{\text{BH}} \lesssim 10^6 M_\odot \), with luminosities less than \( 10^{44} \) erg s\(^{-1}\).
7. Given the typical gas masses of these dwarfs, using a standard Schmidt law for the conversion of gas into stars we estimate star formation rates of the order of \( 30\text{–}60 M_\odot \text{ yr}^{-1} \).
8. If the dwarfs/pre-fragmentation gas clumps remain weakly bound to the protocluster potential, they may form stars and avoid falling back to the central galaxy if strong inhomogeneities in the potential scatter them on to tangential orbits in the protocluster. In such cases, it is conceivable that a trace of this population might be observed even in the local neighbourhood, despite the fact that the tidal forces in the cluster would probably have disrupted the dwarf galaxies themselves. With \( \sim 10^2 \) stars per dwarf, we might expect a few bright planetary nebulae (PNe) per (disrupted) dwarf galaxy. These PNe would contribute to the apparent extragalactic background of PNe detected in local clusters (Ciardullo, Jacoby & Ford 1989; Ciardullo et al. 1998; Ferguson et al. 1998), and would be distinguishable via their clumpy, locally flat density distribution, with small velocity separation, since we expect the internal dispersion of the dwarfs to be small. Even after disruption the stars and hence PN tracers of the stellar population would stay as moving groups, shearing out only over several cluster dynamical times. It is possible that deep imaging would reveal an excess of fainter PNe near individual bright PNe, thereby tracing the stellar population of the dwarf clump of stars.
9. The dwarfs are expected to be detected in the radio (via their low-level emission from the weak central AGN) and in the optical (as a consequence of a burst of star-formation), on being significantly magnified as a result of gravitational lensing, or via narrow-band Ly\( \alpha \) imaging by detecting either the presence of the warm, diffuse gas or emission from the dwarfs undergoing their first episode of star formation.
Despite the fact that the covering fraction along the line of sight to a background QSO of these systems is small, being gas-rich, they might well be detectable in absorption, perhaps explaining the curious fact that the Lyman-limit systems detected by Steidel et al. (1996, 1998) using the colour selection criteria at high redshift ($z \geq 3$) are not the optical counterparts of the absorbers seen in quasar spectra in the same redshift range (unlike the case at low redshifts where such a correspondence has been well established)—pointing to the fact that the absorption at high redshifts is probably being produced by gas-rich galaxies like these dwarfs that have either yet to commence their first episode of star formation or are intrinsically very faint.

### 4.1 X-ray emission predictions

In the following calculation of the X-ray emission, we assume that a virialized cluster has not assembled around the quasar (although the quasar might seed an over-dense region); therefore the X-ray emission arises primarily due to shock-heating of the outflow. During the early adiabatic expansion phase of the hot, shocked layer of the bubble, high temperatures are expected, $\sim 10^8$ K. Therefore, prior to cooling, we expect to see X-ray emission from the hot bubble. We model the density profile of the hot bubble with a constant density out to radius ($R - w$), where $R \sim 1$ Mpc, and $w$ is the width of the shell. Using the standard Hugoniot jump conditions across a strong shock, the shell density at the outer edge is 4 times the central value:

$$n_0(r) = n_0, \quad 0 \leq r \leq (R - w); \quad (10)$$

$$n_0(r) = 4n_0, \quad (R - w) \leq r \leq R. \quad (11)$$

Outside radius $R$, the density is assumed to be that of the ambient IGM. This profile shape is motivated by the density profile found by Bertschinger (1985) for the adiabatic cosmological detonation IGM. This profile shape is motivated by the density profile found by R (1996, 1998) using the colour selection criteria at high redshift, the density is assumed to be that of the ambient medium, which in turn (as can be easily seen from equation 2) leads to the bubble expanding further out to much larger scales, still getting shock-heated to temperatures of a few times $10^8$ K. In that case, the subsequent fragmentation and cooling phases would be delayed. In both scenarios, the optical depth $\tau$ has comparable values, $\tau \sim n_0 R \sim 10^{-3}$; therefore, despite their low X-ray luminosity, these hot bubbles are expected to produce thermal Sunyaev–Zeldovich (S–Z) decrements (due to the scattering of the cool microwave background photons off the hot electrons in the bubble) that may be detectable,

$$\frac{\Delta T}{T} = \frac{2T e^{\frac{kT}{m_e c^2}}}{\tau} = 3 \times 10^{-5} \left( \frac{T}{10^8 \text{ K}} \right). \quad (14)$$

The X-ray emission may be observable over only a small range in redshift, but the temperature decrement may show up at all $z$ as arcminute-scale patches in the cosmic microwave background. A general scenario to explain the detected S–Z decrements (Jones et al. 1997) in the absence of assembled, hot clusters at high redshift from quasar outflows (both a thermal and a kinematic S–Z component) has been explored by Natarajan & Sigurdsson (1998).

The energy available for the scale of outflows proposed here is more than an order of magnitude lower than for the case speculated upon by Natarajan & Sigurdsson (1998), with both $L_{\text{QSO}}$ and $L_\odot$ smaller than envisaged in the earlier paper. They proposed a kinematic S–Z decrement assuming rapid cooling via turbulent mixing, while the decrement in the case discussed here is dominated by thermal S–Z effect that persists till the gas cools to $10^6$ K. A thermal S–Z effect is temporarily observable while the powering QSO is on, and for a short time afterwards, despite the fact that the gas is unbound, because expansion and hence adiabatic cooling is slow in the self-similar expansion regime. Since it takes the gas a

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\begin{align*}
\tau & = 0.1 \quad (r \leq R - w) \\
& = 10^3 \quad (R - w) < r \leq R
\end{align*}$

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\begin{align*}
\Delta T & = \frac{2T e^{\frac{kT}{m_e c^2}}}{\tau} \\
& = 3 \times 10^{-5} \left( \frac{T}{10^8 \text{ K}} \right)
\end{align*}
time $t \sim Rv_c \sim 3 \times 10^8$ yr (where $R$ is the radius, and $v_c$ is the sound speed) to cool, the bubble may stay hot for long enough for a detectable thermal S–Z decrement. During the high-luminosity phase of the QSO powering the outflow, the S–Z thermal decrement would probably be unobservable because of strong radio-lobe emission within the outflow. If the radio lobes fade faster than the gas cools (Rees 1989), then there may be a brief period during which this thermal S–Z effect is observable. In principle, since the frequency dependence of the thermal and kinematic S–Z are different, their relative contributions can be observationally tested.

5 OBSERVATIONAL EVIDENCE

Below, we focus on two recent observations that may be consistent with our proposed picture for the modulated galaxy formation around quasars. Pascarelle et al. (1996) reported the discovery of a possible group of subgalactic clumps at $z = 2.39$ located within 1 arcmin of a weak radio galaxy 53W002. Ly$\alpha$ emission is detected with equivalent widths of approximately 40–50 Å, typical of ionization arising purely from young stars, indicative of star formation activity in these subclumps with inferred stellar masses $\lesssim 10^5$ $M_\odot$ and star formation rates $\sim 50$ $M_\odot$ yr$^{-1}$. The magnitudes of these clumps range from $M_V$ of $-23$ to $-18$, and if the stellar population is assumed to be young, removing the point-source contribution, their inferred luminosities range from 0.1 to 1 $L^*$. Five of these candidates have confirmed redshifts, and three contain weak AGN; the redshift distribution is very narrow, $\Delta z \sim 0.01$, consistent with these clumps being distributed in a sheet geometry around the radio galaxy. Additionally, Hu & McMahon (1996) have detected two objects during a narrow-band Ly$\alpha$ imaging search in a 3.5 $\times$ 3.5 arcmin$^2$ region around a $z = 4.55$ quasar. Both objects are at the same redshift as the quasar. They are separated enough spatially ($\sim 700$ kpc) so that the quasar is unlikely to be the source exciting the observed Ly$\alpha$ emission, and therefore the emission is most probably originating from the star formation activity within these galaxies.

6 CAN WE FORM GLOBULAR CLUSTERS?

Here we speculate on the possibility of the formation of globular clusters (GCs) via the same mechanism, with an attempt to explain the excess number density and possible existence of two distinct populations of GC systems around bright elliptical galaxies. From the scaling arguments presented above, we see that weaker outflows (simply scaling down the parameters in this physical picture) might trigger fragmentation to lower mass clumps, which would stall before escaping from the quasar host galaxy. These lower mass clumps should form near spherical systems with masses $\sim 10^6$ $M_\odot$, since the mutual tidal torquing of the clumps cannot impart any significant spin to them.

Observationally, an excess in the number of GCs associated with bright central galaxies is detected (Whitmore et al. 1996; Forbes et al. 1998), which fits in nicely within this outflow picture. It is possible that some fraction of the population of GCs seen around bright cluster galaxies formed in weaker outflows propagating through the IGM, and that two-phase warm gas subsequently fell back into the central potential after fragmentation and cooling. The fragments, having insufficient velocity to escape the central potential, would stall and collapse in the outskirts of the host galaxy of the quasar, forming a population of nearly coeval, metal-poor, GC-size stellar clumps. Forming with low angular momentum relative to the centre of the potential, the population would assume an $r^{-2}$ density profile with highly radially anisotropic orbits. Any triaxiality of the central potential would isotropize the spatial distribution of the GCs about the galaxy in a few orbital periods, leaving the observed shallow surface density profile of the excess globular population. This scenario therefore predicts that the velocity distribution of the excess globulars ought to be highly radially anisotropic. Recent observational studies of the GC systems around bright ellipticals like M87 (Elson & Santiago 1996) and the ones in the Fornax cluster (Forbes et al. 1998) seem to reveal a clear bimodal colour distribution. In several of these instances, the metal-rich subpopulations are more centrally concentrated than the metal-poor ones (NGC 472 – Geisler, Lee & Kim 1996; NGC 5846 – Forbes et al. 1997; M87 – Elson & Santiago 1996; NGC 3115 – Elson 1997).

Given these detailed observational studies as well as the theoretical multiphase collapse model (consisting of two episodes of GC formation – a pre-galactic assembly phase and a second galactic phase) recently proposed by Forbes, Brodie & Grillmair (1997) for the in situ formation of GC systems around ellipticals, our proposed model is appealing since it provides a physical mechanism to form GCs in the pre-galactic phase.

7 CONCLUSIONS

We have presented a scenario for the formation of baryon-dominated, low-mass dwarf galaxies at high redshift in the vicinity of quasars. The IGM gas mass swept up by the mechanical luminosity of the outflow from the quasar forms a thin dense shell that expands adiabatically until the age of this gas bubble approaches the Hubble time at the given redshift, $z$, at which juncture the shell fragments due to a Jeans-type gravitational instability producing a characteristic clump mass of $10^5$ $M_\odot$, leading to the formation of a group of dwarf galaxies in a sheet-like geometry on roughly an arcminute-scale around the quasar. We predict the properties of this high-surface-brightness, low-mass, high-redshift dwarf population, and demonstrate that the optimal detection strategy would be narrow-band Ly$\alpha$ imaging in the regions around high-redshift quasars. Examining the feasibility of detection in the X-ray during the early adiabatic expansion phase of the hot bubble, we find that direct X-ray emission is likely to be detectable only from low redshifts ($z < 1$), while measurable thermal S–Z decrements on arcminute-scale patches in the cosmic microwave background are expected from all redshifts. Finally, we argue that a scaled-down version of the same outflow picture could lead to a fragment mass that is typical of GCs, therefore providing a possible physical mechanism for the formation of the older metal-poor, pre-galactic GC population.

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