Dark Galaxies and Lost Baryons
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"Dark Galaxies" and Local Very Metal-Poor Gas-Rich Glaxies: Possible Interrelations

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Abstract. There are only a few "dark galaxy" candidates discovered to date in the local Universe. One of the most prominent of them is the SW component of a merging system HI 1225+01. On the other hand, the number of known very metal-poor gas-rich dwarfs similar to I Zw 18 and SBS 0335–052 E,W has grown drastically during the last decade, from a dozen and a half to about five dozen. Many of them are very gas-rich, having from ∼90 to 99 % of all baryons in gas. For some of such objects that have the deep photometry data, no evidences for the light of old stars are found. At least a half of such galaxies with the prominent starbursts have various evidences of interactions, including advanced mergers. This suggests that a fraction of this group objects can be a kind of very stable protogalaxies (or "dark galaxies"), which have recently experienced strong disturbances from nearby massive galaxy-size bodies. Such a collision caused the gas instabilities and its collapse with the subsequent onset of starburst. We briefly discuss the morphology and gas kinematics for the subsample of the most metal-poor dwarfs that illustrate this picture. We discuss also the relation of these rare galaxies to the processes by which "dark galaxies" can occasionally transform to optically visible galaxies.

Keywords. Galaxies: formation, evolution, interactions, dwarf, starburst, abundances, peculiar

1. Introduction

The possible existence of a large number of dark galaxies was suggested to reconcile the drastic difference between the predicted number density of low-mass Cold DM halos and the observed number density of low-mass galaxies (e.g., Klypin *et al.* (1999), Moore *et al.* (1999)). Despite the fact that the gap diminished significantly during the last years thanks to discovery of many very low-mass galaxies in the Local Group (e.g., Moore, this meeting), it is still too large. The observational methods of searching for dark galaxies were discussed, e.g., by Trentham *et al.* (2001). The range of global parameters, in which one expects the dark galaxies to exist, was explored in Verde *et al.* (2002), Taylor & Webster (2005) and Davies *et al.* (2006) based on one of CDM models of disk galaxy formation by Mo *et al.* (1998). While the predictions of the original version of Taylor & Webster (2005) work differed strongly from those of Davies *et al.* (2006), the revised analysis by E. Taylor (this meeting) resulted in similar ranges of dark galaxy global parameters.

2. Dark Galaxy candidates vs model-predicted objects

There are a few Dark Galaxy candidates known to date. We summarize some of their observational parameters in Table 1. Three of these four objects were discussed during this Symposium in the talks given by M. Haynes, J. Davies and E. Brinks. No optical counterparts were found for any of them. The upper limits on their central surface brightness (SB) are at the levels of 27–27.5 V-mag sq.arcsec^{-2} (Salzer *et al.* (1991),

Table 1. Main parameters of candidate dark galaxies

Name	M(HI)[1]	V_{rot}[2]	M_{bar}/M_{tot}	HI col.dens.[3]	Lin.size[4]
HI 1225+01 SW	2.8-11.2	13	**0.4-1.0**	<3-4	17-34
VIRGOHI 21	0.4	100	**0.002**	0.3	14
HIJASS J1021+6824	1.5	40	0.036	1.8	30
HI J0325–3655	2.2	<20	>0.1	0.2	16

[1] in units 10^8 $M_\odot$, [2] in units km s^{-1}, [3] in units 10^{20} at. cm^{-2}, [4] in kpc.

Minchin *et al.* (2005), Walter *et al.* (2005)), except HI J0325–3655 near FCC 35, for which no optical counterpart is visible on the SERC images (Putman *et al.* (1998)). The distance-dependent parameters for HI 1225+01 SW are given for two possible distance extremes of 10 and 20 Mpc. V_{rot} is estimated either from the velocity fields, or from the maximal velocity widths. The first glimpse on the table reveals a rather large scatter of main parameters for these candidates. In addition, the new data presented at the Symposium, suggests that HIJASS J1021+6824 along with many smaller HI features can have the tidal origin due to the strong interactions in M 81 group (Brinks, this meeting). Moreover, according to the ALFALFA HI map, VIRGOHI 21 looks like a part of a long tail stretching from the massive spiral NGC 4254 (R. Giovanelli, this meeting) which is probably an evidence against its dark galaxy nature.

On the other hand, there are ΛCDM N-body simulations mentioned above, predicting the regions of the parametric space of baryon aggregates in which one can expect to find dark galaxies, defined as baryon "disks" inside DM halos with no stars formed so far. Therefore, it is reasonable to compare these predicted properties with those of "dark galaxy" candidates and of some their possible descendants. Since as told in the Introduction, both Davies *et al.* (2006) and Taylor (2007, this meeting) give in general the consistent ranges of main parameters of dark galaxies, we base our further on the published results of Davies *et al.* (2006). They can be summarized as follows. The total range of M(HI) is of 10^5 to 10^9 $M_\odot$, with only ∼2% of simulated objects to have M(HI)=10^8-10^9 $M_\odot$. HI column densities vary in the range of $(0.5–5)\times10^{20}$ at. cm^{-2}. The range of V_{rot} is of 5 to 70 km s^{-1}, with less than ∼1% to have $V_{rot} > 30$ km s^{-1}. The accepted baryon mass fraction (M_{bar}/M_{tot}) according to theoretical expectations varies between 0.01 and 0.05.

Comparing the observed properties of candidate "dark galaxies" with those predicted from the N-body simulations, one concludes that they do not match each other well. The observed HI masses are too large. Could this be happening partially due to a selection effect? Or are we (mainly) dealing with "wrong" candidates? On the other hand, accounting for possible descendants of dark galaxies among XMD galaxies (see Sect. 4), many of which are also "massive", are we that confident about the predicted mass range of dark galaxies?

If VIRGOHI 21 is a dark galaxy, its M_{bar}/M_{tot}=0.002 appears to be atypically small. On the other hand, if HI 1225+01 SW (∼0.5), is a real dark galaxy, this parameter is also a challenge for commonly-accepted models. Can such a high baryon mass-fraction be observed only in transient entities (e.g., "tidal dwarfs") characteristic of interacting systems? If one of new XMD BCGs (see Table 4) and two new HI-rich isolated dwarf galaxies with similar baryon mass-fractions found in ALFALFA (M. Haynes, this meeting) are real, they probably prove that such rare objects can exist as stable aggregates. If this is true, then we can say that HI 1225+01 SW is a real dark galaxy being witnessed in the process of its merging with the other gas-rich (and very metal-poor) object.

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3. eXtremely Metal-Deficient (XMD) galaxies: summary of properties

Due to space limitations, we only give here a very brief summary of XMD galaxy properties closely related to the further discussion. The great majority of late-type XMD galaxies known to date (conditionally, with metallicities Z of $Z_\odot/34$ to $Z_\odot/10$, where $Z_\odot$ corresponds to 12+log(O/H)=8.66) are classified as blue compact galaxies (BCGs) which are low-mass starbursting galaxies. They represent the very edge of the general BCG metallicity distribution (peaked at $Z{\sim}Z_\odot/5$) and comprise only ∼2% of all known BCGs. Their number known to date is about a half a hundred.

For "quiescent" late-type dwarfs, there exists a well known rather tight luminosity-metallicity (L–Z) relation (e.g., Skillman *et al.* (1989)), which is applicable over ∼7 magnitudes in *B*-band and 1.5 dex in O/H. A couple the dimmest dI galaxies, UGCA 292 and Leo A ($M_B \sim -11.5$) show Z as low as $Z_\odot/25$ (12+log(O/H) ∼7.3). The origin of this L–Z relation is usually explained in terms of a slower astration in low-mass galaxies and partlially by the elevated metal loss in the smallest galaxies. A similar L–Z relation for BCGs does exist, albeit with much larger scattering and with a shift to the higher luminosities at a fixed O/H. These scattering and shift are especially large in the XMD regime (see, e.g., a bit out-of-date Figure in Pustilnik *et al.* (2003)). To emphasize the large difference between XMD dIs and BCGs, we compare their baryon masses. As follows from Table 2, the range of these XMD BCG baryon masses M_{bar}, accepted as M(gas)=M(HI)+M(He), equals ∼(2.6–12) $\times10^8$ $M_\odot$. For the most metal-poor dIs Leo A and UGCA 292, the M_{bar} are ∼0.1 and 0.5×10^8 $M_\odot$, that is on average more than an order of magnitude smaller.

The global parameters of XMD BCGs show very large diversity. For their small metallicity range (a factor of ∼3), their L_B and M(HI) vary in the range of 150 and 200, respectively. M(HI)/L_B varies between <0.2 to 8 (in solar units). For several XMD BCGs the gas mass-fraction ($M_{gas}/(M_{gas}+M_{stars})$) is found to be as high as 0.95-0.99 (see summary, e.g., in Pustilnik & Martin (2007)). Morphologies of XMD BCGs vary from regular to typical mergers. All this implies probable inhomogeniety of XMD BCGs on their evolutionary path-ways. An additional evidence for this are the colours of their outer parts which vary from red to very blue (in few galaxies). This implies that the majority of XMD BCGs are rather old, while a fraction of "very blue" gas-dominant XMD BCGs can be rather "young" (namely, their "first stars" ages $T* <$ 0.5-2 Gyr << 13.5 Gyr).

4. Interactions/mergers in XMD BCGs

The importance of interactions for BCG starbursts in general was discussed by many authors (e.g., Pustilnik *et al.* (2001a) and references therein). For XMD BCGs, interaction-induced starbursts are currently known to take place in at least a half of this group. Curiously enough it appears that all six of the most metal-poor BCGs, with 12+log(O/H)=7.12–7.29, show various signs of interactions/mergers. We summarize their parameters in Table 2. Due to lack of space we do not show the images with optical/HI morphology and kinematics. Part of them are published, while the rest will be presented soon elsewhere. Below we give some notes on these galaxies. The unique merging XMD galaxy pair SBS 0335–052 E,W with gas mass-fractions of 0.96 and 0.99 provides the best polygon to confront models of very gas-rich mergers with real objects. The existence of this and another merging system HI 1225+01, in which the NE component is also an XMD galaxy and the SW component is a "dark galaxy" candidate, suggests that there are "special" space regions in which such atypical objects are more abundant and, thus, can be found in a mutual collision. There are indications that XMD galaxies probably favour the void-like

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Table 2. Main parameters of six the most metal-poor BCGs

Name	O/H	M(HI)	M_B	V_{rot}	Dist	M_{bar}/M_{tot}
SBS 0335–052 W	7.12	9.0	−14.7	37	53	0.2
DDO 68	7.14	7.0	−15.5	51	10	0.2
I Zw 18	7.17	2.5	−15.2	44	18	0.1
UGC 772	7.24	2.4	−14.4	20	14	
SDSS J2134–0035	7.26	2.0	−13.8	58	20	0.7
SBS 0335–052 E	7.29	8.0	−16.9	32	53	0.2

O/H - in units 12+log(O/H) from Izotov *et al.* (2005), Izotov *et al.* (2006) and Izotov & Thuan (2007), M(HI) - in units 10^8 $M_\odot$ from Pustilnik *et al.* (2001b), Pustilnik *et al.* (2005), van Zee *et al.* (1998), Schneider *et al.* (1991), and data in preparation, V_{rot} in km s^{-1}, Distance in Mpc. V_{rot} for SBS 0335–052 E,W and UGC 772 are lower and M_{bar}/M_{tot} are upper limits, since the inclination correction is uknown.

environment (e.g., Pustilnik *et al.* (2005), Pustilnik *et al.* (2006), Pustilnik & Kniazev (2007)). Since the galaxy number density in voids is higher near the borders, one can expect to detect such objects in transition layers of void regions.

Summarising, we conclude that previous (e.g., van Zee *et al.* (1998), Pustilnik *et al.* (2001b), Pustilnik *et al.* (2005) for I Zw 18, SBS 0335–052 E,W and DDO 68) and new (Ekta *et al.*, in prep. for UGC 772 and SDSS J2134–0035) observational data indicate that starbursts in all the lowest metallicity (O/H $<$ 7.30) XMD BCGs, which are "massive" objects with M(gas) of (2.6–12)$\times 10^8$ $M_\odot$, are related to mergers and strong interactions. Their "high" baryon and total masses imply that the metal loss due to galactic winds does not affect their chemical evolution. Therefore, their extremely low metallicities suggest that their progenitors are very stable and have produced very few stars/metals (if any at all) in previous epochs. Hence, they should be either very low surface brightness galaxies or a kind of protogalaxies, which escaped strong external disturbance. If some of the XMD BCGs are indeed "young", then dark galaxies are the natural candidates to be their progenitors. They could become "visible" due to recent strong interactions.

5. Dark Galaxy collisions: an empirical approach and need for models

It is evident that dark galaxies (DG) are treated as superstable against gas collapse only if taken as "isolated" objects (e.i. when the external perturbations are smaller than internal ones). Collisions of a fraction of DGs with galaxy-sized objects should affect their stability and induce the sinking of gas to their centers and its collapse. One can suggest three empirical levels of disturbance due to gravitational interaction: *significant, strong* and *merger*. We call collision/interaction "significant" if it triggers gas collapse and SF and elevates the stellar mass and related (central) surface brightness above the "threshold" level, say of μ =26.5 B-mag sq.arcsec^{-2}, which is characteristic of the extremely LSB galaxies. How much such an object would resemble known ELSBGs, depends on its SB radial profile. For the case of "strong" collision/interaction, DG will transform to an object with a more typical central SB, say with μ =23–25 B-mag sq.arcsec^{-2}. Their resemblence to known LSBGs again depends on the resulting SB radial profile. In the case of a merger of a DG and another galaxy-sized aggregate, the results can be rather different depending on the type and mass of the said counterpart. Such an event can be accompanied by a significant starburst and for some cases can look like a XMD BCG.

It is interesting to note that result of "significant" interaction can be transient if a DG keeps its internal stability after the collision. After 0.5–1 Gyr all massive and intermediate mass newly formed stars will die and the light of this "ELSB" galaxy will fade below $\mu =$ 27.5 B-mag sq.arcsec^{-2}. The object again will be transformed to a dark galaxy.

This discussion of various galaxies, which could be in principle related to a population of dark galaxies in the local Universe, shows a serious need for numerical models of dark galaxy interactions. While the simulations of very gas-rich galaxy collisions have been difficult until recently due to the problem of proper accounting for various feedback processes, there has been significant progress made over the last two years. Springel & Hernquist (2005) and Robertson *et al.* (2006) presented N-body simulations of interacting gas-rich galaxies (with 99% of baryons in gas) which reproduce the formation of a disk galaxy in a major merger. Up to now the models have dealt with rather massive objects. There is a need to extend them to the region of expected "dark galaxy" parametric space. This will allow one to better understand what emerges from their interactions: more or less "typical" LSBGs or something unusual. The models of "dark galaxy" mergers will elucidate whether some of XMD BCGs may be related to this process.

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