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Assessing the state of galaxy formation.

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Abstract. We present the results of a survey of nearby, quiescent, non-peculiar, extremely isolated galaxies to search for the gaseous remnants of galaxy formation. Such remnants are predicted to persist around galaxies into the present day by galaxy formation models. We find low-mass H I companions around 7 of 34 galaxies surveyed. In addition we find 5 galaxies with lopsided H I distributions. The implications for galaxy formation and the nature of high velocity clouds are discussed.

1. Introduction

What is the current state of galaxy formation in the local universe? There have been many recent detections of H I clouds near larger spiral galaxies in the local universe. Such detections include H I clouds around NGC 925 (Pisano, Wilcots, & Elmegreen 1998), IC 10 (Wilcots & Miller 1998), four of five barred Magellanic spirals (Wilcots, Lehman, & Miller 1996), four of 16 low surface brightness dwarf galaxies and four of nine H II galaxies (Taylor *et al.* 1993, 1996), and high-velocity clouds (HVCs) around M101 (Kamphuis 1993), NGC 628 (Kamphuis & Briggs 1992, and in our own Local Group (see Wakker & van Woerden 1997; Blitz *et al.* 1999). Typical clouds have 10^7-$10^8 M_\odot$ of H I amounting to 1%-50% of the mass of the primary galaxy.

In numerous cases these H I clouds have been suggested to be remnant material from the galaxy formation process (e.g. NGC 925, IC 10, NGC 628, etc...). Current models of cold dark matter galaxy formation in which disk galaxies were built up via the accretion of smaller bodies in a hierarchical merging process predict such remnant material to exist (e.g. Navarro, Frenk, & White 1995). Unfortunately the serendipitous nature of these detections inhibit our ability to divine the true origin of the H I clouds. These H I clouds could be primordial material, but could also be material ejected via a galactic fountain or superwind, tidal debris from a recent interaction, or simply a small dwarf galaxy companion. Therefore, few, if any, of the H I clouds represent unambiguous detections of the remnant reservoir of gas from which galaxies formed.

To determine what the current state of galaxy formation is, we have conducted a systematic search for the remnant gas around a sample of extremely isolated and quiescent galaxies. The results from the pilot survey of six galaxies were reported in Pisano & Wilcots 1999, here we report of the current status of the expanded survey.

2. Sample

In order to determine the origin of H I clouds around other galaxies it is important to have a well-defined sample. We chose galaxies from the Nearby Galaxies Catalog (Tully 1988). The galaxies were classified as isolated such that they had no known companions with $M_B \leq$-16 mag within 1 Mpc of them. In addition, galaxies were chosen that were classified as non-peculiar. These two conditions minimize the chance of the galaxy having had a recent interaction or merger so there should be no tidal debris around our sample galaxies. Our galaxies were also chosen to be quiescent (i.e. not Seyferts or starbursts) so that any gas around these galaxies is unlikely to be galactic ejecta from a galactic fountain or superwind.

Finally, galaxies were chosen such that they were large enough and close enough to resolve with the VLA in D configuration and the ATCA .750 configuration ($D_{25} \geq 1'$, R$\leq$45 Mpc), yet far enough away to probe out at least 90 kpc (R$\geq$21 Mpc). This left us with 60 galaxies in the entire sky; we observed 34 of those galaxies

3. Observations

Between November 1997 and February 2000 we observed a total of 34 galaxies with the VLA and ATCA. A total of 600 km s^{-1} was covered at a resolution of 5.2 km s^{-1} for each observation. The sample galaxies had distances between 21 Mpc and 45 Mpc, allowing us to survey out to a radius of 92 - 192 kpc at a resolution of $\sim$1$'$(6.1-12.8 kpc). The resulting observations have $\sigma \simeq$0.5-1$\times$10^{19}cm^{-1} per channel for the column density. The mass detection limits are 8.3$\pm$3.5$\times$10$^6 M_\odot$ for a 5σ detection over 2 channels (10.4 km s^{-1}). The range of mass detection limits comes from varying sensitivity and distance for each galaxy.

4. Results

Of the 34 galaxies surveyed we detected gas-rich companions in H I around 7 of them (see figures 1 & 2). Another 5 galaxies have "disturbed" H I morphologies (figures 3 & 4); either severe warps or lopsided distributions possibly indicative of a recent minor merger. The remaining 22 galaxies are relatively normal with all of the idiosyncrasies we typically see in galaxies such as small warps and asymmetries.

The detected companions have $M_{\rm H\ I}$ between $10^8 M_\odot$ and $10^9 M_\odot$, which corresponds to 3%-30% of the primary galaxy's mass in H I. The companions appear show signatures of rotation, so based on the rotation widths and sizes of the companions we determined their dynamical masses to be between $10^9 M_\odot$ and $10^{10} M_\odot$, which is 0.5%-10% of the main galaxy's dynamical masses. The

Figure 1. UGC 11152, an isolated galaxy accreting a gas-rich companion. The left panel is total H I intensity on an optical image from the Digital Sky Survey with contours starting at 10^{19}cm^{-2} with increments of a half a dex. The right panel is the H I velocity field on top of the H I total intensity. Some velocity contours are labeled for reference. Contours are spaced by 20 km s^{-1}.

Figure 2. NGC 2708, an isolated galaxy interacting with a gas-rich companion. Panels are as in figure 1.

ratio of H I mass to dynamical mass for the companions range from 7%-85%. All H I clouds detected have spatially coincident optical emission, with the possible exception of UGC 11152. All of these properties are consistent with the gas-rich companions being typical dwarf galaxies.

This does not, however, mean that we have not detected the gaseous remnants of galaxy formation, but simply that these gas clouds formed stars before being accreted by the primary galaxy. It is important to confirm, however, that these gas-rich companions will eventually be accreted. Our companions have projected separations of 20-100 kpc (1-6 R_{gal}) in radius and 20-100 km s^{-1} in velocity. These numbers imply an orbit time, which is roughly equal to the dynamical friction timescale, of 5-10 Gyr. These companions turn out to be in relatively stable orbits.

5. Implications for the nature of High-Velocity Clouds

The Blitz *et al.* (1999) model for the origin of HVCs in the Local Group suggests that they are primordial material left over from the formation of the Local Group. In this model HVCs are at large distances from the Milky Way (R$\sim$750kpc-1Mpc) and, therefore, have large masses ($M_{\rm H\,I} \sim 10^7 M_\odot$).

While our survey was not optimized to examine the origin of HVCs, there are some intriguing implications from its results. We detected no objects that resembled HVCs (i.e. no gas-rich companions without stars). Furthermore, we detected no companions smaller than $10^8 M_\odot$ in H I down to our detection limit at $\sim 10^7 M_\odot$. This implies that if HVCs are associated with galaxy formation, they must either have masses lower than $10^7 M_\odot$ and/or be at projected separations greater than 140 kpc. The former suggestion is somewhat unlikely, because we do detect larger companions and while one might expect more H I clouds at lower masses, we do not detect any down to our detection limit. Another possible explanation for our non-detection of HVCs is that they are associated with group formation, and not with the formation of individual, isolated galaxies. Either way, any explanation for a primordial origin of HVCs in the Local Group must account for our non-detection of them around isolated galaxies.

Figure 3. IC 5078, an isolated galaxy with a "disturbed" H I morphology. Panels are as in figure 1.

Figure 4. NGC 895, a severely warped isolated galaxy. Panels are as in figure 1.

6. Implications for Galaxy Formation

The main goal of this work was to assess the state of galaxy formation in the local universe. At this point in time, this work has yielded three main implications for galaxy formation:

First, galaxy formation appears to be an efficient process. As discussed above, we found no companions with H I masses below $10^8 M_\odot$ implying that there is not a population of low mass H I clouds within ∼100 kpc of these galaxies.

Second, galaxy formation has basically concluded. Only ∼20% of isolated galaxies have low-mass (∼10%M_{gal}), gas-rich companions, (which are in stable orbits). Therefore most of the gas must already be in the main galaxy. The mass outside of the main galaxy will take a long time (∼5 Gyr) to be accreted.

Third, galaxy formation may have recently ended. Another 15% of isolated galaxies have disturbed H I morphologies suggesting that they may have recently (in the last 1 Gyr) undergone a minor merger (≤10% M_{gal}).

The accretion rates implied by this work (10% of M_{gal} over 6 Gyr for ∼40% of galaxies) are consistent with those derived by Toth & Ostriker (1992) from the scale height of the Milky Way, Zaritsky & Rix (1997) from the frequency of asymmetries, and Navarro, Frenk, & White (1995) from galaxy formation simulations. Future work on this project will involve further increasing the number of galaxies surveyed, comparing the stellar properties of the main galaxies and companions with their H I properties and more detailed comparisons of our detection rates with theoretical predictions.

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