HI-selected Galaxies As a Probe of Galactic Disks

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We investigate a link between the Ly-alpha absorption systems and local galaxy population in the hierarchical structure formation scenario using semi-analytic galaxy formation models, by drawing a detailed comparison between the properties of the HI-selected galaxies and the Damped Ly-alpha absorption (DLA) systems.

By making a comparison with the observational results of the blind radio surveys (e.g., the Arecibo Dual-Beam Survey and the HI Parkes All Sky Survey) and the surveys for the optical counterparts (e.g., the Survey for Ionization in Neutral Gas Galaxies), we find the basic properties of the HI-selected galaxies :

(1) the star formation rates (SFR) correlate strongly with the HI masses; SFR $\propto$ M(HI)^p with p=1.3-1.4 in the range of HI mass from 10^6 to 10^{11} $M_\odot$.

(2) the cross-sections of the galactic HI disks (the HI column density > 10^{19} cm^{-2}) correlate tightly with the HI masses; $\sigma \propto$ M(HI) in the range of HI mass from 10^6 to $10^{10.5}$ $M_\odot$,

We also find that, while DLAs consist of the population of the local HI-selected galaxies at M(HI)>10^8 $M_\odot$, sub-DLA systems comprise mainly the galaxy population at M(HI)~10^7 $M_\odot$.

The HI-selected galaxies at M (HI)=10^7 $M_\odot$ would be a strong probe of sub-DLA systems that place stringent constraint on the key processes of galaxy formation and evolution.

§1.Introduction

Why do we focus on DLA systems?

1. High HI-gas column densities N(HI)>$10^{20.3}$cm^{-2}
2. High number densities at high redshift (DLA systems vs massive L* galaxies)

$$\left(\frac{dN}{dz}\right)_{DLA} \approx 10\left(\frac{dN}{dz}\right)_{typical\ galaxy}$$

3. Precise measurements of metal abundances in gaseous component at high/low redshifts
   e.g. ZnII (unaffected by dust depletion)
   mildly metallicity evolution (0.5 <z< 4.5)
4. Dust-poor system (cf: typical galaxy)
   Small amount of dust (e.g. ~1/10 (Our galaxy))

>> DLAs is a Good Tracer of Star Formation history of Pre-galactic systems
>> Constraint on Galaxy Formation

§ 2. MODEL

● **Merging Process of dark halos**

Probability Function f(M,z | M',z')dM:
dark halo (mass M' redshift z') has a progenitor (M,z)
>> Press-Schechter Mass Function n(M,z | M',z')

Methods (redshifts z' to z (z'<z))

1. Monte-Carlo realization as probability variables M
2. Count progenitors (Vc > 40 km/s)
(dark halos with Vc < 40 km/s accrete into central halos)
3. Realize above processes for each progenitor at higher redshifts

● **Physical Processes**

(A) Life time of halo is equal to cooing time of gas

$$t_{life} = \tau_{cool}(r_{cool}) = \frac{2}{3}\frac{\rho_{gas} r_{cool}}{\mu m_p}\frac{kT}{n_e^2 r_{cool}\Lambda(T)} \qquad (\rho_{gas}(r) \propto n_e(r) \propto r^{-2})$$

(B) star formation timescale

$$\tau_* = \tau_*^0\left(\frac{V_c}{300km/s}\right)^{\alpha_*} \qquad \tau_*^0, \alpha_*$$

(C) SN feedback: Energy input by SNe

$$\frac{dM_{rehaeat}}{dt} = \varepsilon\frac{4}{5}\frac{\eta_{SN}E_{SN}}{V_c^2}\dot{M}_*\left(=\beta\dot{M}_*\right) \qquad \beta(V_c) = \left(\frac{V_c}{V_{hot}}\right)^{-\alpha_{hot}} \quad V_{hot}, \alpha_{hot}$$

(D) Population Synthesis: Total Luminosity

$$L_* = \int \dot{M}_* Z_{cold} dt$$

(E) Chemical Evolution Basic Equation for 2 phase model (Cold and Hot gas components)
Here we apply 'Instantaneous Recyclic Approximation'.

$$\frac{dM_c}{dt} = -\dot{M}_* + F(t)(1-f) + g(t) - \beta\dot{M}_*$$

$$\frac{dM_*}{dt} = \frac{M_c}{\tau_*}$$

$$\frac{dM_h}{dt} = \beta\dot{M}_* - g(t) + F(t)f + A(t)$$

$$g(t) = 4\pi\rho_h(r_{cool})r_{cool}^2\frac{dr_{cool}}{dt} \cong \frac{M_c^0}{\tau}$$

$$\frac{dM_cZ_c}{dt} = (1-f)(F_Z(t)+R_Z(t)) - Z_c\dot{M}_* + Z_h g(t) - Z_c\beta\dot{M}_*$$

$$\frac{dM_hZ_h}{dt} = f(F_Z(t)+R_Z(t)) + Z_c\beta\dot{M}_* - Z_h g(t) + Z_d A(t)$$

Astrophysical parameters are given by as follows:
1. Galaxy luminosity function (B- and K- bands) ⇒ α_{hot},V_{hot} (<< SN feedback process)
2. HI-mass function & Cold-gas mass fraction of local galaxies ⇒ α_*

● **Merging Processes of galaxies**

・Hot gas is incorporated with a new common halo
・Two types of merging process between galaxies: (major & minor merge)
Merging between galaxies with similar mass merge(Major merge) : Star burst, Bulge formation
Other merging (Minor merge): small galaxies are incorporated with a disk of large galaxies: Disk formation

● **Dust extinction** :phenomenological model with galactic extinction curve and slab model(Wang & Heckman 1996)
opacity is proportional to luminosity $\tau \propto L^\beta$ (β=0.5)

● **DLA systems:**

(1) The radial distribution of N(HI) follows an exponential profile (2) the effective radius $r_e=r_0(1+z)$ where r0 is provided by the specific angular momentum conservation of cooling hot gas. (3) the spin parameters has a lognormal distribution. (4) The size is defined by the radius R at Log N(HI)=20.3 cm^{-2} (5) The column density is averaged over radius within R (6) random realizations of the disk inclinations when we calculate the HI column densities of galactic disks.

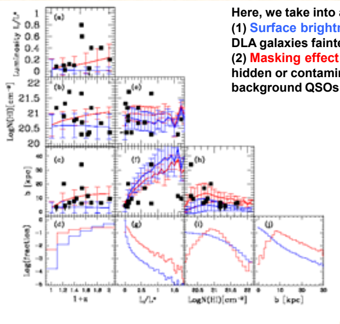
MODEL PARAMETERS
Ω_0=0.3, Ω_Λ=0.7, h=0.7, σ_8=1
V_{hot}=320 (240) [km/s], α_{hot}=2.5, τ_*^0=1.5[Gyr], α_*=-2(Model High Star formation [HS])
-3 (Model Low Star formation [LS])

§ 3. RESULTS

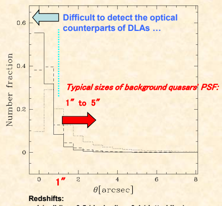
[A] BASIC PROPERTIES OF DLA SYSTEMS AT LOW REDSHIFTS

We focus on DLA systems at redshift 0<z<1
・Luminosity, HI column density, size etc.
The photometric counterparts (e.g. Rao et al.2003 ;Chen et al. 2003,2005)

Here, we take into account selection effects of DLA galaxies
(1) Surface brightness dimming effect: fail to identify DLA galaxies fainter than observational brightness limits
(2) Masking effect prevents us from identifying DLA galaxies hidden or contaminated by a point spread function of background QSOs



The basic properties of DLA galaxies for our model taking into the selection effects of both masking and dimming effects (red) and without any selection effects (blue), respectively. The squares indicates observational data compiled by Rao et al . (2003).



Redshifts:
z=1 (solid), z=0.5 (dashed), z=0.1 (dotted line)

・We find that our results show better agreement with the observations when the selection effects are taken into account (e.g. angular size limit 1″ & surface brightness limit 25 mag arcsec^{-2}) .

・The number fraction of masked DLA galaxies reaches 60-90% in the sample when the angular size limit is as small as 1″, corresponding to the scale at most ~6 kpc at z=0.5 and ~8 kpc at z=1, in addition to the surface brightness limit 25 mag arcsec^{-2} .

(Okoshi and Nagashima 2005, ApJ, 623, 99)

[B] Radio properties of DLA systems at redshift z=0

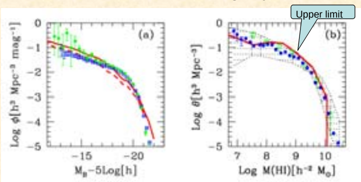
Another way to exploring DLA systems apart from the selection effects.

Detections of DLA galaxies by blind radio surveys (e.g., the HI Parkes All Sky Surveys (HIPASS); the Arecibo Dual-Beam Survey (ADBS); the Survey of Ionization in Neutral Gas Galaxies (SINGG))

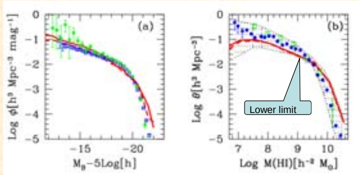
⇒ More than 4000 HI-rich galaxies vs the 10-20 optical counterparts of DLAs (Ref; e.g., Zwaan et al. 2005, MNRAS,364,1467)

⇒ *How many DLAs contribute to the galaxy population ?*

First, we focus on the basic properties of galaxy population; Luminosity functions, HI mass functions (HIMF), & Cold Gas Mass-Luminosity ratios.



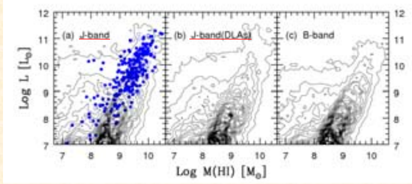
(a) The Luminosity functions of galaxies (solid) and DLAs (dashed) for Model LS. Observations: 2dF(open circles) and ESP (closed circles)
(b) The HI mass functions of galaxies (solid) and DLAs (dashed) for Model LS. Observations: HIPASS (Zwaan et al. 2005; closed circles) and ADBS (Rosenberg & Schneider 2003; open circles). Model LS gives an upper limit of the observed number density at M(HI)=$10^9 M_\odot$ where the mean number density in the blind radio survey .



(a) The Luminosity functions of galaxies (solid) and DLAs (dashed) .for Model HS.
(b) The HI mass functions of galaxies (solid) and DLAs (dashed) for Model HS. Model HS gives a lower limit of the observed number density at M(HI)=$10^9 M_\odot$ where the mean number density in the blind radio survey .

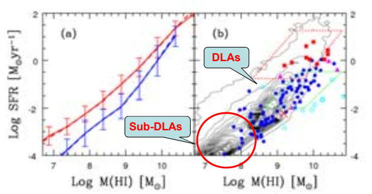
Our model shows good agreement with the basic properties of local galaxies selected by both optical and radio surveys.

NO differences between galaxies and DLAs.....



The luminosity distributions as a function of HI masses for Model LS. (a) The J-band luminosities of (a) galaxies, (b) DLAs and (c) the B-band luminosities of galaxies. The dots indicate the J-band luminosities of HI-selected galaxies based on blind radio surveys (e.g., the Arecibo Dual-Beam Survey data).

The HI-selected galaxies provide good clues to revealing the nature of DLAs.



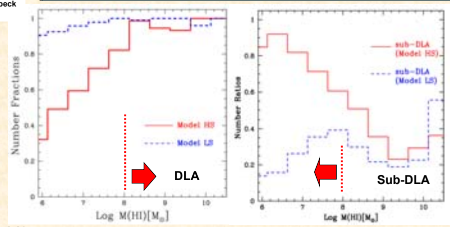
a) Star formation rates in galaxies as a function of HI mass at redshift z=0 for Model HS (red solid-line) and Model LS (blue solid-line). The star formation rates in DLA galaxies are also shown for Model HS (red dashed-line) and Model LS (blue dashed-line).
(b) The contour map for the SFR vs the HI mass in galaxies for the LS model.
The star formation rates of the sample provided by the Survey for Ionization in Neutral Gas Galaxies are shown as filled circles (Meurer et al. 2006). The star formation rates provided by optical and infrared surveys are also presented as open circles (van Zee et al. 1997), filled triangles (O'Neil, Oey, & Bothun. 2007) and filled squares (Rahman et al. 2007). The star formation rates in the HOPCAT galaxies obtained from the infrared survey (red dotted-box) and the radio ones (green dotted-box) are also presented (Doyle & Drinkwater 2006). A star formation rate in an optical counterpart of a DLA system is plotted as a cross (Schulte-Ladbeck et al. 2004).

HI-selected galaxies provide a clue to exploring what morphological types of galaxies consist of DLAs

Star formation rates (SFRs)
•The mean SFR is 0.01 $M_\odot$ yr^{-1}.
•*The SFRs correlate strongly with the HI masses;*
SFR $\propto$ M(HI)^p; p=1.25±0.05 (Model HS) 1.40±0.07 (LS)

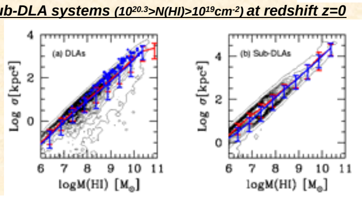
We also find that DLAs contribute PARTLY to the local galaxy population: M(HI) > $10^8 M_\odot$

Sub-DLAs (19 <Log N(HI) <20.3) would replace DLAs as the dominant population in the low-mass end (M(HI)~$10^7 M_\odot$).

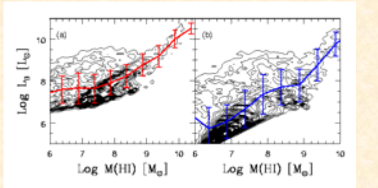


The HI-selected galaxies at the low-mass end (M(HI)~$10^7 M_\odot$) would be a good probe of sub-DLAs .

[C] Sub-DLA systems ($10^{20.3}$>N(HI)>10^{19}cm^{-2}) at redshift z=0



(a)The cross sections of DLAs in our model (red) and our model but α_*=-3 (blue). Observations: the ADBS blind surveys (Rosenberg & Schneider 2003; dots) We find NO DIFFERENCE between the models with DIFFERENT SFRs. Our results are consistent with the observations of DLA cross-sections.
(b) The cross sections of sub-DLAs in Model HS (red) and LS (blue).



The B-band luminosities of sub-DLAs in (a) Model HS and (b) Model LS, respectively. The solid lines represent the mean luminosities with 1-σ error bars.

We find that
(1) A tight correlation between the HI masses and the cross sections: $\sigma \propto M(HI)^\alpha$; α=0.97-0.98(DLA) & 0.92-0.96(sub-DLA)
(2) The low luminosity galaxies with small impact parameters (~ 3 h^{-1}kpc) mainly consist to the DLA population.
(3) The mean HI masses are $10^9 M_\odot$ (DLA) and $2\times10^8 M_\odot$ (sub-DLA), respectively.
(4) Sub-DLA systems (M(HI)~10^7 $M_\odot$) would comprise faint galaxies (~$4\times10^8 L_{B\odot}$) with impact parameters (~ 4 h^{-1}kpc) .
(cf. Briggs & Barnes 2006; Tripp et al. 2005)
(5) The mean metallicities of cold gas are <Log Z/$Z_\odot$>= – 0.51±0.40 (DLA) and –0.48±0.38 (sub-DLA).

⇒ Our results are consistent with the observational properties of HI-selected galaxies in the radio surveys.

§ 4 Conclusion

We investigate a link between galaxies and quasar absorption systems using hierarchical galaxy formation models taking into account merging processes of dark halos.

● Our model reproduces basic properties of local galaxies in both optical and radio blind surveys.
・Luminosity functions, HI mass functions, and Cold gas mass-Luminosity ratios.

● DLA systems primarily consist of low-luminosity galaxies with small impact parameters (typical radius 3 h^{-1}kpc, HI mass $10^9 M_\odot$, surface brightness from 22 to 27 mag arcsec^{-1}) with the typical star formation rate (SFR) about 0.01 $M_\odot$yr^{-1}.

● The masking effect significantly affects the identification of DLA galaxies at redshift z<1
⇒The number fraction of masked DLA galaxies reaches 60-90% when low-luminosity galaxies with small impact parameters(~3 h^{-1}kpc) primarily give rise to damped Ly α absorption lines in quasar spectra.

● Our results suggest the following relationships for the optical counterparts of HI-selected galaxies detected in blind radio surveys (e.g., HIPASS & SINGG).
・The star formation rates correlate with the HI masses: SFR $\propto$ M(HI)^p; p=1.3-1.4
・The cross section of HI-disk sizes (<10^4 kpc^2) correlates tightly with the HI mass: $\sigma \propto$M(HI).

● DLA systems consist of the HI-selected galaxies at M(HI)>10^8 $M_\odot$. By contrast, Sub-DLA systems would replace DLA systems as the galaxy population at M(HI)~10^7 $M_\odot$ under the detection limit of current blind radio surveys.

● *The basic properties of dwarf galaxies (e.g., luminosity functions, SFRs, and metallcities) would be revealed by exploring sub-DLA systems in the radio and optical surveys.*