The faint HI environment of galaxies: a laboratory for testing galaxy formation

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The SKA is a unique instrument to open a window on many aspects of galaxy formation and evolution which can be examined in our Local Universe. Here I will focus on the outermost regions of galaxies which can be observed with sufficient sensitivity and resolution at 21-cm as to enlighten the interplay between galaxies and the intergalactic gas, the competing race between the local dark matter gravity and the external ionizing radiation field. Tracing the gas distribution out to large galactocentric radii will be complementary to QSO's Lyα absorption studies for understanding the evolution of the dark and visible matter of the Universe.

1. Introduction

The faint gaseous envelopes of galaxies are important sites for studying the processes which are at the heart of galaxy formation and evolution. They connect the bright active star forming regions to their larger cosmic environment, made of gas, dark matter and photons, through which galaxies are forming. The absence of strong star formation activity in these regions makes them suitable for disentangling the cosmological variables from local processes. Sensitive surveys of the outer regions of galaxies are needed in order to derive from them unique information, such as the interplay between galaxies and the intergalactic medium, the size and structure of dark matter halos, and the relevance of collisional and photoionization processes for the evolution of cosmic structures. Possible local disturbances, such as those related to the proximity of a central star forming region or to close encounters between galaxies, can be fully understood and modeled only through a wide survey of galaxy morphologies and environments.

In the following Sections I will outline in more detail the need for observing the 21-cm emission of the gas in the outer regions of galaxies down to column densities $\sim 10^{17}$ cm^{-2} with the high sensitivity and resolution that SKA will provide. Current deep 21-cm surveys with single dish telescopes are sensitive to column densities $N_{HI} \simeq 1-5\times 10^{18}$ cm^{-2} but the large beam width limits the information one can derive on the kinematics and distribution of the neutral gas (Minchin et al. 2003). High resolution imaging with beam sizes $\leq 1'$ has usually been done for column densities higher than 2×10^{19} cm^{-2} (e.g. Hunter & Wilcots 2002, Wilcots & Hunter 2002). The actual number of galaxies mapped with spatial resolution of order of 1 kpc and a sensitivity in the range 1-5$\times 10^{18}$ cm^{-2} is very limited since this requires a large amount of telescope integration time or the galaxy must be located in our close neighborhood (confusion with emission of the Milky way halo is of major concern in this case).

2. 21-cm emission maps and QSO Ly-alpha absorption lines: different probes of similar structures in the evolving Universe

2.1. Intervening absorption systems in QSO spectra

Current progress in the theoretical framework have been made to understand high redshift optical observations which gave indirect evidence of the presence of faint condensations along the line of sight to QSOs. These condensations have been modeled as filaments connecting the IGM to the high density contrast central regions, which is where star formation takes place. Gas condensations may flow in and out the galaxy potential well and direct imaging of the 21-cm emission will hopefully enlighten the radial components of the velocity field of the galaxy low density environments (see Braun, this Volume, for addressing this SKA science case). However there is no compelling evidence of these structures yet and it is also not well understood how they connect to the brighter central regions.

Although Lyman-α absorption line studies are well suited for tracing the column density distribution of the HI gas at various cosmological epochs for column densities $N_{HI} < 10^{17}$ cm^{-2}. Statistics for higher column densities are more difficult. This is because Lyman-α absorption lines are not suitable for a determination of N_{HI} when $10^{17} < N_{HI} < 10^{20}$ cm^{-2} and lines are in the flat part of the curve of growth. Gas clouds in this column density regime show optical depths $\tau > 1$ to the quasar ionizing radiation and will make a break in the quasar spectrum at the frequency corresponding to the Lyman edge (Lyman limit systems). Only for $\tau \sim 1$ can N$_{HI}$ be measured accurately. Larger τ values imply that Lyman limit systems can be detected but N$_{HI}$ cannot be measured. Therefore the HI column density distribution in this regime is poorly known, not only because of the limits on today's 21-cm emission surveys, but also because of the undetermined value of N_{HI} in intervening QSO absorption systems.

2.2. Ionization processes

It is of great importance to have detailed information on the HI column density distribution for $10^{17} < N_{HI} < 10^{20}$ cm^{-2}. This lies not only on the relevance of knowing the baryonic and dark matter boundaries of galactic type structures, but also on the fact that this regime connects the mostly neutral part of the gas distribution to the highly ionized side of it. Therefore knowing the details of the gas distribution in this regime will open a window on the ionization processes acting in the outskirts of galaxies. Important ingredients for galaxy formation, such as the UV background radiation field, the escaping fraction of UV photons from star forming disks, and the presence of collisional ionization from violent relaxation will be enlightened. This information is also essential for deriving the total gas column density distribution and hence the gas baryonic content of our Local Universe. Theoretical models and the two high resolution observations of the HI distribution along one side of the major axis of M33 and NGC3198 have shown that in outer disks N_{HI} drops by one order of magnitude in less than one beam size (about 1 and 3 kpc respectively for the two observations) as the column density approaches the face on value of 2×10^{19} cm^{-2} (Corbelli & Salpeter 1993, Maloney 1993). This drop has been interpreted in terms of a sharp HI/HII transition due to photoionization from UV extragalactic background radiation. Modeling a sharp edge in detail for deriving the extragalactic radiation field intensity requires a knowledge of the possible contamination from nearby UV sources, of the radial scale length of the HI gas distribution where the gas is mostly neutral, and a knowledge of the dark matter density near the edge (the latter because the ionization-recombination balance depends also on the gas volume density which is a function of the gravitational potential). This explains the need for observing a large sample of objects to disentangle all the variables. A new statistical approach for deriving some information on the ratio between the ionization field intensity and the gravity in intervening QSO absorbers has been developed by Bandiera & Corbelli (2001). However, it is only by inferring the properties of the hosting dark matter halo through accurate 21-cm maps of the velocity field in outer regions that the radiation field intensity can be recovered. Figure 1 shows this together with the need for N$_{HI}$ data close to the HI photoionization threshold for drawing definite conclusions on the ionization processes and on the total density of baryons in our Universe. The next generation of H-α detectors will certainly complement the above research (e.g. Tufte et al. 2002).

2.3. Dark matter halos

Today's sensitivities and resolutions, together with the uncertainties on the stellar mass to light ratio, do not allow us to test the validity of dark matter models which predict a cusp in the center of dark matter halos. The consistency of these models with the actual data requires generally very low values of the halo concentration (e.g. de

Blok et al. 2001, van den Bosch & Swaters 2001, Corbelli 2003). This in turn implies that rotation curves should be sampled with higher resolution in the inner regions but especially they should be extended to larger radii in order to reach regions where the dynamical contribution of the stellar disk is negligible compared to that of the halo. Many galaxies today still show a smooth rising or flat rotation curve at the outermost sampled radius. By extending maps of the outer regions by two orders of magnitude down in HI column density with respect to today's measurements we will be able to detect the stronger decline of the dark matter density with radius. The most promising cases for detecting the decline of the rotation curve will be those galaxies with the highest value of dark matter concentration.

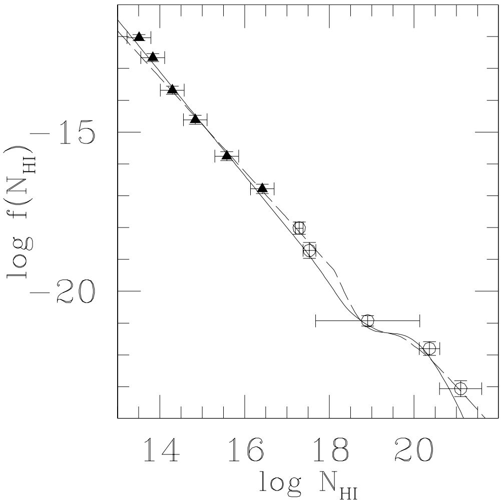

Figure 1. Data and two best fitting models for the N$_{HI}$ distribution function in our Local Universe. Filled triangles are from the compilation of Lyα forest data by Weymann et al. (1998), open circles are from the Lyman-limit and damped Lyα systems catalog of Corbelli et al. (2001). Both the continuous and dashed line functions fit the actual data quite well but they correspond to two different ionization models and to two different total gas densities (see Corbelli & Bandiera (2002) for details). This figure shows the need for HI data for N$_{HI}$ $> 10^{17}$ cm^{-2} to constrain the models.

3. First experiment: beyond the star forming regions

3.1. Goals

Through observations of the outskirts of galaxies, described in this Section, one should be able to derive important information on the dark matter, on the extragalactic ionizing radiation and other ionizing processes in the Local Universe. In particular one can establish:

–If there is a flattening in the total N_{HI} distribution for $N_{HI} < 10^{20}$ cm^{-2} and the HI column density where it possibly occurs. This flattening should be present if photoionization processes are relevant in the outskirts of galaxies.

–If there are ionization edges in the HI distribution of single galaxies and if their properties are universal or depend on local and environmental conditions.

–How does the amplitude and the smoothness of rotation vary with galactocentric radius well outside the region where the stellar disk dynamics is dominant.

–If there is any evidence of gas circulation from or towards the brighter star forming regions.

–The outer disks morphology: thermal phases, clouds mass, spiral arms, flaring.

3.2. Observing strategies

We need to observe a large sample of galaxies in order to disentangle the extragalactic background ionizing radiation from other sources of ionization (UV photons escaping from nearby star forming regions, turbulent mixing layers from collisional ionized hot gas...) and to avoid the possible degeneracy with an undefined dark matter density distribution. The ideal sample will comprise galaxies of similar masses but with different levels of star formation activity as well as galaxies with different estimates of the dark matter density in the outer regions (accessible with today's sensitivities) and in different environments. In order to define the structural properties of dark matter halos, galaxies with a low ratio of visible to dark matter and with extended HI disks need to be sample. Also important is to extend the HI maps of those galaxies which show high values of the dark matter concentration since for those galaxies the probability of detecting the boundary of the dark halo is higher.

In order to build up an N_{HI} distribution function our observation should sample the whole range of HI mass with a well known HI mass function. Galaxies should be sampled with a spatial resolution comparable with the HI scale length. If the ionization edge happens to be present, then the scale length of the HI distribution is about 1 kpc and observations of outer regions for this large sample should be carried out with a limiting N_{HI} sensitivity of 10^{18} cm^{-2}.

The observations should be carried out with a channel width lower than the thermal speed of the medium and which would also be sufficient for deriving the kinematic information. Taking 2 km s^{-1} spectral channel resolution for a typical line width of 30 km s^{-1}, a SKA spatial resolution of 30 arcsec requires an integration time of about 4 hours for a 3-σ detection of 10^{18} cm^{-2} column densities, given the actual design specifications. Target galaxies will be located in the nearby 10 Mpc Universe but the total large SKA bandwidth will sample for free a much deeper volume in z. Therefore this experiment can be done in conjunction with searches for very low surface brightness objects.

4. Second experiment: from galaxies to the IGM

4.1. Goals

In this second experiment one would like to observe the 21-cm emission which originates from HI gas at column densities as low as 10^{17} cm^{-2}. In this regime the following features should be detectable:

–Where do disks end i.e. how disks connect with IGM filaments and if there is evidence of material falling into the galaxies from the intergalactic medium.

–The slope of the N_{HI} distribution function for $N_{HI} \sim 10^{17}$ cm^{-2}. Here the ionization fraction is high and it does not vary so rapidly with the total gas column density as for higher N_{HI} values. This, together with QSO absorption data for lower HI column densities and with N_{HI} data from the first experiment, will allow us to define unambiguously the HI-Htot relation and therefore the total gas content of our Universe (see Figure 1). If the dark matter-gas scaling relation holds, one can derive the matter density and check the compatibility of the ionization models with the adopted cosmology.

4.2. Observing Strategies

From the large survey done in the first experiment, observers pick up the most representative candidates for carrying out the deeper integration. As one goes towards HI column densities lower than 10^{18} cm^{-2} (where the HI/HII transition is taking place), the steeper slope of the N_{HI} distribution function ensures that the sky area filled with such a low density gas will increase as N_{HI} decreases. Therefore one doesn't need to survey large sky areas as for the first experiment. The likely spatially fragmented HI distribution which will characterize this regime implies however that a few areas should be sampled for averaging out local perturbations and orientation effects and reducing the errors in the N_{HI} distribution.

With a beam size as large as 100 arcsec observers should be able to sample the gas distribution with a sensitivity (at the 3σ level) which is 10^{17} cm^{-2} for 21 hours of integration (assuming a 50 km s^{-1} signal width, and 10 km s^{-1} spectral resolution). This experiment can be done in conjunction with filament searches in the local Universe.

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