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Title HI research in the era of SKA pathfinders

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This paper briefly reviews the evidence for gas removal and gas accretion processes in galaxies from sensitive resolved HI observations with existing telescopes. This is basically a preview of how HI can be used to characterise the evolutionary state of a galaxy and gives the perspective of the scientific power of the SKA (Square Kilometre Array) pathfinders, and eventually the SKA itself, for using HI observations of galaxies to characterise their evolutionary state and the processes that are of importance for this.

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1. Introduction

The prediction [35] and first detection [10, 22, 27] of the 21-cm transition of neutral atomic hydrogen (HI) has been very important for radio astronomy and opened an area of active research using the HI line to characterise the detailed distribution and kinematics of the diffuse ISM in the Milky Way [37] and other galaxies [14, 30, 38, 40]. Single dish surveys such as HIPASS [43] and ALFALFA [13] continue to provide information about the general HI content of thousands of galaxies, while high resolution imaging in HI of a much smaller number of galaxies (~ 400) has contributed immensely to our understanding of a variety of physical processes that are important for shaping galaxies: the kinematics has been used to probe the detailed mass distributions in galaxies [3, 23, 33]; the distribution and kinematics of the HI combined have probed tidal interactions, and several other gas accretion and removal processes in and around galaxies [29]. The increased sensitivity of existing high resolution instruments has enabled a preview [33, 34] of what new facilities will be able to deliver for thousands of galaxies once major surveys commence. This contribution briefly summarises the present state of affairs regarding HI research and describes what we can expect from the facilities that become operational in the coming years [8, 9, 15, 26]. Its focus is what we have learned from resolved HI imaging about galaxy evolution.

2. Results from resolved HI imaging

Resolved observations of the HI in galaxies now exist for a few hundred galaxies, partly from a small number of large observing programs [14, 29, 38, 40] and from a number of indivi-

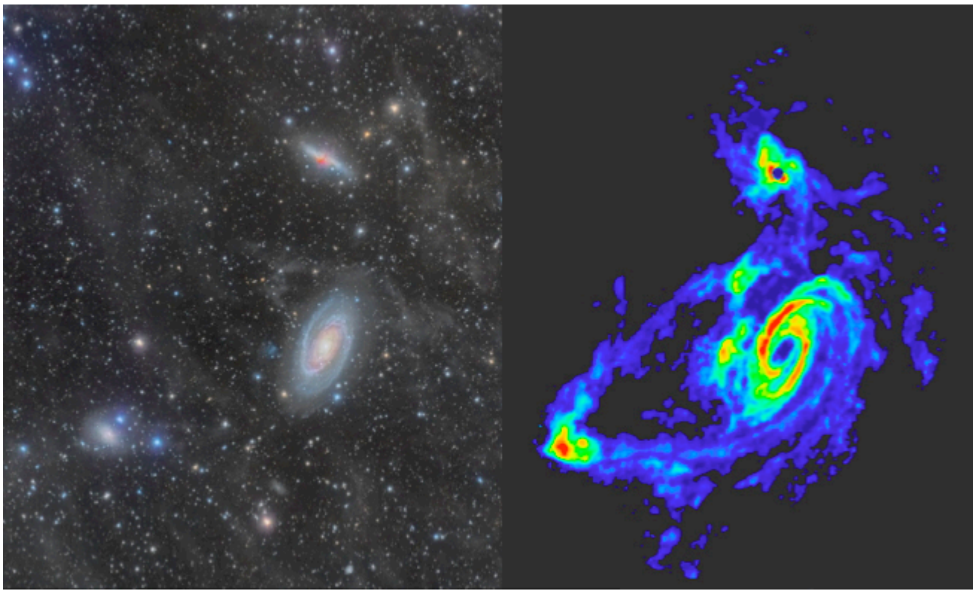

Figure 1. Optical image (left panel) and HI image (right panel [42]) of M81, M82 and NGC 3077. The HI image very clearly shows the effects of tidal interactions. The optical image does reveal some outlying material, but is much less revealing than the HI and does not provide any kinematical information.

dual studies. These have been used originally to study the dark matter distribution in galaxies [3, 23, 33]. The emphasis has gradually shifted to using the HI to probe the effects of the environment, interactions, and the accretion of outlying material. HI studies play an increasingly important role in assessing the importance of gas removal and gas accretion mechanisms in galaxies. These are crucial for galaxy evolution and have been incorporated in most modern simulations of the evolution of galaxies [17, 39]. It is very clear that knowledge of the HI is an essential component for understanding galaxy evolution, complementing information at other wave bands, which probe the stellar population (UV/optical/near-IR), the dust (mid-IR/far-IR/submm), the molecular gas (submm) and the hot ISM (X-rays). Figure 1 illustrates this complementarity beautifully. Side by side it shows the optical image and the HI image of M81 and its immediate environment. A comparison of the HI in M 83 with the distribution of UV emission (Figure 2) is another clear demonstration of the great importance of multi-wavelength observations. M 83 appears to have a large, warped outer HI disk with a wealth of spiral-like structure, which does exhibil low level star formation as demonstrated by the UV emission.

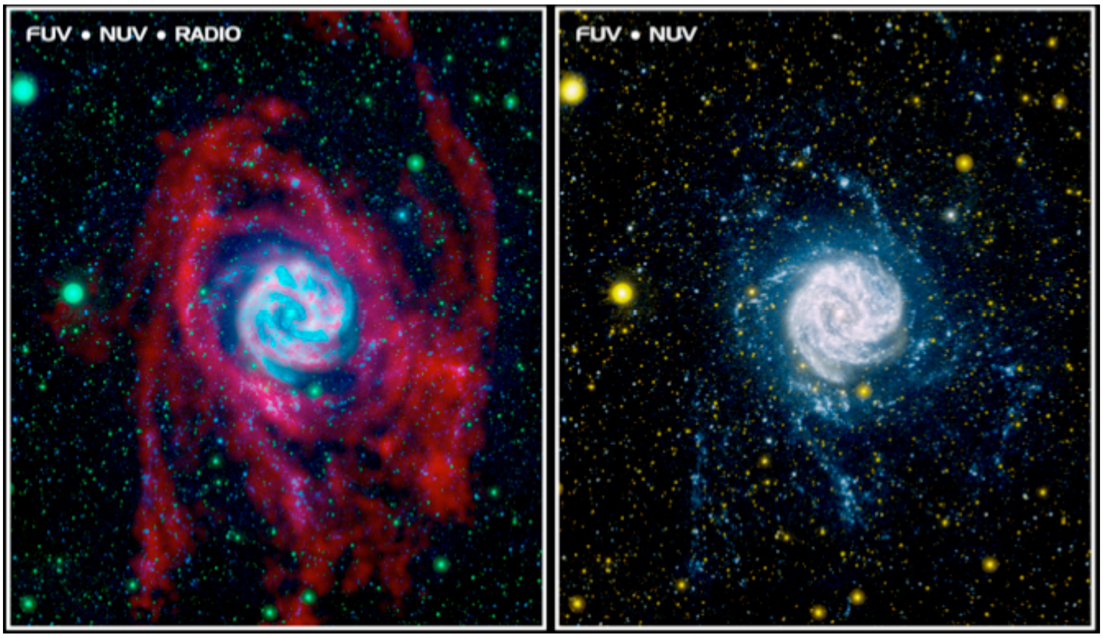

Figure 2. HI image [40] superposed on a near- and far-UV composite image [1, 35] of M 83 (left *panel)*. For better comparison of the faint outer structures the single UV composite image is shown as well (right *panel)*. Note the arms, arcs, filaments in the outer disk, visible in both the HI and the UV images, indicating that even in the faint outer HI star formation is progressing (Courtesy Dave Thilker and NASA/JPL-Caltech/VLA/MPIA)

A number of phenomena relevant to understanding the role of gas for galaxy evolution and discovered in HI observations have been described in a recent review [29]. These are: (i) the presence of warps in about half the HI disks; (ii) the lopsidedness of many galaxies, both in terms of the HI distributions and in terms of the overall kinematics; (iii) the discovery of HI with anomalous velocities and of extra-planar HI; and (iv) the presence and structure of extended low column density HI features around galaxies. All can be interpreted as the signatures of gas removal and/or gas accretion mechanisms.

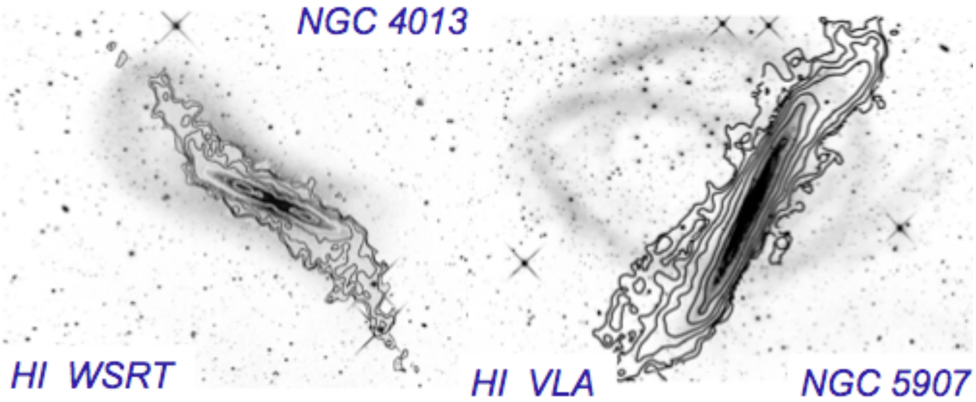

Figure 3. Warped HI column density distributions overlaid on deep optical images illustrating the presence of stellar streams [4, 20, 21, 31]. NGC 4013 is shown in the left panel, NGC 5907 is shown in the right panel.

2.1 Gas accretion

Gas accretion is manifest in many ways. Lopsidedness of galaxies and the presence of warps can both result from a minor merger, the accretion of a small, presumably gas rich galaxies or even steady accretion of material from the cosmic web [29]. The galaxies in Figure 3 are both warped in HI [4, 31] and it is tantalising to associate the warp phenomenon with the very faint stellar streams [20, 21] that have been discovered optically around these galaxies. These galaxies could be an example of tidally induced warps, although by very minor companions that now no longer exist. Not enough cases have yet been studied in detail to provide a consistent picture of gas accretion. The main problem is that the required column density sensitivities demand long integrations (well over 100 hours), which has not yet been done for many objects. The HALOGAS project [14] has observed a sample of some 20 galaxies for over 100 hours each at the WSRT and is expected to provide further insights.

Other evidence for gas accretion has come from very deep observations of the edge-on galaxy NGC 891 [24]. The push to lower HI column density ($\sim 10^{19}$ cm^{-2} in this case) has led to an increase of the HI extent perpendicular to the plane, but not in the radial direction. In addition to its lopsidedness in the radial direction NGC 891 now shows an extended (to ~10 kpc above the plane) halo of neutral gas with a complex filaments reaching beyond this halo to ~20 kpc above the plane. Figure 4 illustrates these components. The 5 kpc halo appears to consist of gas that co-rotates with the disk [34] albeit slower and is presumably the result of a 'galactic fountain'. Such a lagging halo has also been found in NGC 2403 [11,12]. The most exciting feature is the gas at anomalous velocities, not co-rotating with the disk, and shown in the right panel of Figure 4. The peculiar velocities indicate that this gas has not yet settled in the galaxy's potential and hint at an external origin. The amount of anomalous velocity gas is about 10^8 $M_{\odot}$, with individual gas complexes of about 10^6 $M_{\odot}$.

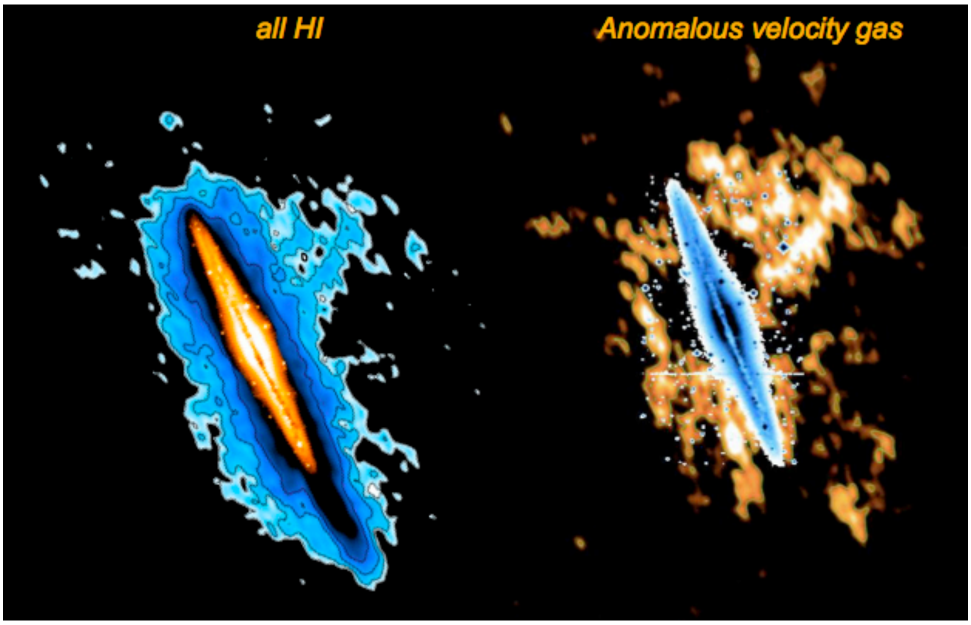

Figure 4. *Left panel:* Optical DSS image (orange) and total HI map (contours + *blue shade)* of the edge-on galaxy NGC 891. HI contours are 1, 2, 4, 8, 16 × 10^{19} cm^{-2} [24]. The beam size is 25" or 1.1 kpc. *Right panel:* Optical DSS image (blue) and HI at anomalous velocities in orange.

2.2 Gas removal

The classical gas removal mechanisms are tidal and ram pressure stripping. Tidal stripping has most prominently been demonstrated in the Virgo cluster [6, 16, 25], which has been studied in great detail and continues to be a very interesting and nearby laboratory for studying galaxy evolution in a dense environment. Figure 5 clearly shows that ram pressure stripping reduces the relative size of the HI disks in the core of the cluster as compared to those in the outskirts. Two galaxies clearly experiencing ram pressure [16, 25] are highlighted. An example of tidal stripping is shown in Figure 1. The difference with ram pressure stripping is that much of the material remains bound to the galaxies and will eventually fall back. This influx of gas cannot always be distinguished easily from accretion out of the surrounding cosmic web.

A milder form of gas removal is the 'galactic fountain' transferring gas out of the disk into the galactic halo. This phenomenon has been clearly seen in NGC891 [24, 34], NGC 2403 [11, 12] and NGC 6946 [2]. This gas is temporarily removed from the process of star formation, but may eventually return to the disk. Interestingly a recent theoretical study [19] suggests that this process enhances the general accretion of gas from the halo. This increases the complexity of unravelling the overall picture of gas removal and gas accretion using HI observations.

3. SKA Pathfinders

Several upgraded and new facilities will be available for high resolution HI imaging in the next 5-10 years: the upgraded VLA (Jansky VLA), the upgraded WSRT with the phased array feed system APERTIF [26], the Australian SKA pathfinder ASKAP [8] and the South African telescope MeerKAT [9, 15]. The latter two systems will be incorporated in SKA phase-1. While the strength of ASKAP and APERTIF is the large field of view enabling surveys of large areas of sky, the complementary strength of MeerKAT and the J-VLA is the high sensitivity, enabling deep observations of restricted areas of sky. Before the end of the decade these facilities will have begun to carry out (i) blind surveys of large fractions of the sky at moderate sensitivities (~10^{20} cm^{-2}), providing resolved HI images of more than ten thousand galaxies in different environments, and (ii) deeper (~ 2×10^{19} cm^{-2}) surveys of restricted areas, still spanning several hundred square degrees, providing deep images for at least a thousand galaxies. These will provide the kind of information discussed in section 2 for thousands of galaxies in many different environments and make it possible to identify which processes of gas removal and accretion play an important role when and where.

The large single dish FAST [28], under construction in southern China, will add important information about the very low column density gas around nearby galaxies and will be capable of detecting the lowest HI mass galaxies ($M_{HI} < 10^6\ M_{sun}$) in the local universe, improving the results from HIPASS, ALFALFA and similar single dish surveys.

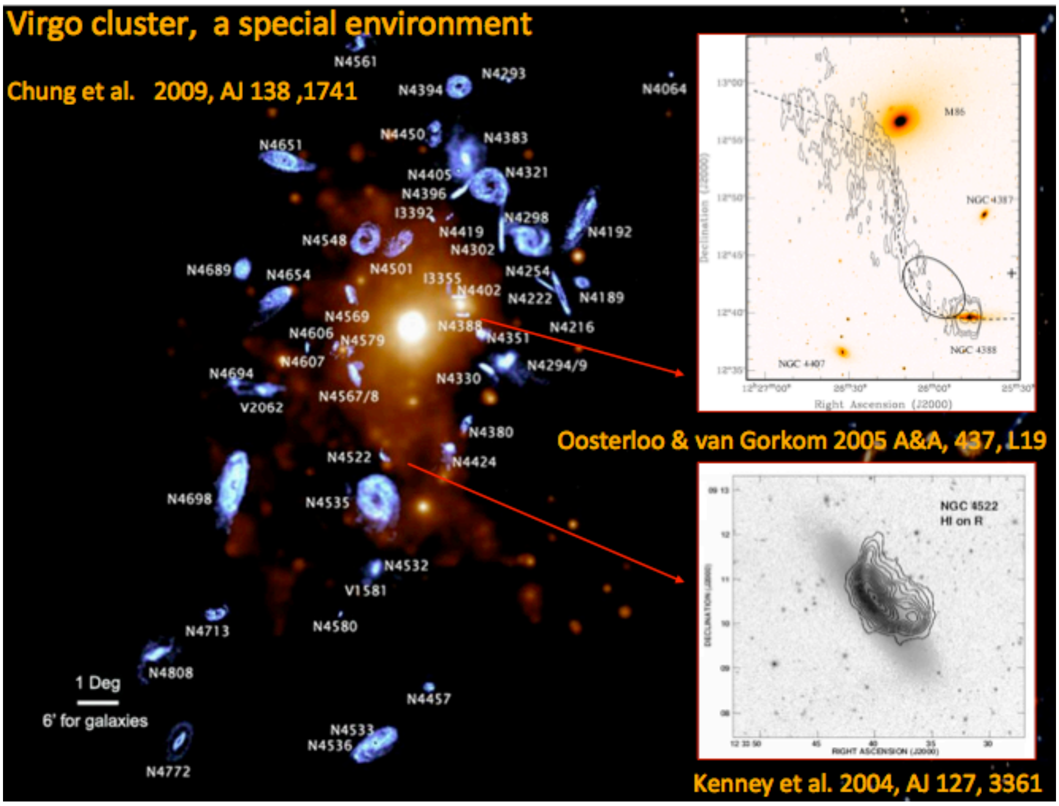

Figure 5. Rosat X-ray image (orange) of the central part of the Coma cluster with total HI images (blue) from [6]. The HI images have been enlarged by a factor 10 to display the details better. Note the variety of morphologies and the trend toward smaller HI disks in the cluster core. The inserts show NGC 4388 (top right) and NGC 4522 (bottom right), prime examples of ongoing ram pressure stripping [16, 25].

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