The ISM in Nearby Galaxies

Elias Brinks [a]

[a]INAOE, Puebla, Mexico, ebrinks@inaoep.mx

The SKA will revolutionise the study of the principles underlying Star Formation (SF), resolving interstellar cloud complexes which are the birthplaces of stars and answering such questions as which are the sufficient and necessary conditions for SF to commence. Also, massive SF is intimately related to stellar death. The SKA will be able to study the structure of the ISM at 100 pc resolution out to distances of up to 20 Mpc and will quantify the impact the demise of massive stars has on their environment. Importantly, the SKA will probe the transition region between ISM and IGM, linking star formation and stellar death in the disks of galaxies to faint HI structures further afield, such as "anomalous gas" and (Compact) High Velocity Clouds. Lastly, the superb sensitivity of the SKA will result in some hundred background sources per square degree against which HI absorption lines can be searched for, probing not only the relative importance of the different phases of the gas in galaxies but also the low density gas in the outskirts and between galaxies.

1. Understanding Star Formation

Star formation is arguably the single most important process to shape the Universe as we know it. The very first luminous objects, through their ionising radiation field, put an end to the "Dark Ages". Star formation in the first structures that formed caused (proto–)galaxies to light up, creating the stunning, galaxy studded images in deep exposures revealed by HST. And it is star formation that enriches the interstellar and intergalactic medium (ISM and IGM, respectively) with metals and which continues to change the balance between the amount of matter within galaxies and the number of stars.

Despite the obvious importance of the star formation (SF) process, embarrassingly little is known about the sufficient and necessary condition for SF to commence. To improve this situation, high spatial and velocity resolution maps are required which resolve the individual cloud and cloud complexes of atomic hydrogen (HI) which will collapse to form stars. It is from these neutral cloud complexes that giant molecular clouds will condense. As their linear sizes are of order 100 pc, this requires an angular resolution of $1''$ at a distance of 20 Mpc. In other words, in order to understand SF at a cosmological level, studies of nearby galaxies are indispensable and are our only way to address questions such as what triggers the onset of star formation: is it due to a local gravitational instability or does one need an external driver, for example an interaction, is it triggered by density waves or rather a bar instability? What is the role played by magnetic fields (Beck & Gaensler, this volume). Closely related to this is the question of how SF depends on galaxy environment, galaxy type, galaxy kinematics and heavy element abundance of the ISM.

The SKA will be the only instrument capable of reaching the required resolution at sufficient sensitivity within an acceptable amount of observing time. Assuming that 50% of the total array collecting area will fall within a diameter of 6 km and 75% within a diameter of 30 km, taking $\mathrm{A}_{eff}/\mathrm{T} = 20000\,\mathrm{m}^2\,\mathrm{K}^{-1}$ between 0.5 and 1.5 GHz, and hence $\mathrm{A}_{eff} = 2.5 \times 10^5\,\mathrm{m}^{-2}$ and taking as a maximum baseline 45 km in order to achieve a $\theta_{syn} = 1''$, a 12 hr targeted observation at 10 kHz ($2\,\mathrm{km\,s}^{-1}$) velocity resolution will reach a 3σ limit on the surface brightnesses within a single channel of typically 10 K. A $\theta_{syn} = 1''$ corresponds to 0.25 pc at the distance of the Magellanic Clouds (50 kpc), 18 pc at the distance of the M81 group (3.6 Mpc), and 50 pc at 10 Mpc.

There are over a thousand galaxies of all Hubble types within 10 Mpc. The Virgo cluster is included if extending the range to 20 Mpc at which distance the linear resolution is still an acceptable 100 pc, comparable to the published studies in M31 and M33 (Brinks & Bajaja 1986, Deul & den Hartog 1990).

In order to cover galaxies of all Hubble types over a wide range of surface brightness, metallicity and star formation activity, a sample of at least 100 objects will be required, e.g., along the line of the *Spitzer Space Telescope* SINGS Legacy project (Kennicutt et al. 2003; Walter et al. 2004) which translates to a 1200 hr project. A project of this nature would, of course, benefit from a large ($\sim 1^{\circ}$) instantanuous field of view as well as from multiple fields of view.

It is illustrative to show what can be done currently and what the SKA will achieve. Fig. 1 is an HI peak brightness map of the LMC (Kim et al. 1999) at a resolution of $1'$ or 15 pc and represents one of the highest linear resolution maps of an object in the Local Group. The SKA will allow the resolution to be increased 60–fold in the case of the Magellanic Clouds, whereas the resolution currently obtained in the Clouds will be achieved in galaxies within 4 Mpc. Moreover, with a resolution of $1''$ one can do the same kind of studies in external galaxies out to 4 Mpc as what has been done with 100–m single dish telescopes such as the GBT or Effelsberg at the distance of the center of the Milky Way.

The view is that star formation occurs above a certain gas column density threshold (e.g., Kennicutt 1989, Martin & Kennicutt 2001). The SKA will be able to answer the question if there is a "universal" star formation threshold, and to what extent this threshold is a function of galaxy type and of heavy element abundance. Studies of low metallicity systems, such as dwarf irregular (dIrr) galaxies, can be used to extrapolate to SF in the unenriched early universe. This study will benefit from synergies with other future instruments such as ALMA which will provide the necessary high resolution observations of the molecular gas, at comparable resolution.

Integrated HI surface density maps will be combined with velocity dispersion maps and the derived rotation curves to calculate spatially resolved "Toomre–Q" parameter maps for each galaxy (the Q parameter is a measure for the local gravitational balance; Toomre 1964). An example of what will be possible is presented in Fig. 2 for the galaxy NGC 6822 (de Blok & Walter 2000). Using these kind of maps the question can be addressed what the importance is of local (disk or cloud instability) versus global effects (spiral density waves, tidal forces, magnetic fields) in triggering SF.

2. The Violent Interstellar Medium

Star birth is intimately related to star death. The most massive stars (with masses larger than 8 $M_{\odot}$) explode as type II supernovae and deposit of order 10^{51} erg of kinetic energy in their immediate surrounding creating coronal gas filled, overpressured bubbles which expand into the surrounding ISM. These bubbles show up as empty regions in HI (HI bubbles or superbubbles, depending on their size). A spectacular example is again the LMC, an image of which is reproduced in Fig. 3 (Kim et al. 2003). The expanding, shocked rims where subsequent star formation is likely to occur, are known as giant or supergiant shells. The superbubbles and supergiant shells are thought to be due to the combined effect of multiple SNe occurring within a young stellar association (i.e., within a short time span and within a limited volume). The accumulated energy is sufficient to blow superbubbles which grow larger than the thickness of the disk of a typical spiral galaxy, launching the expanding shell and enriched, hot gas into the halo.

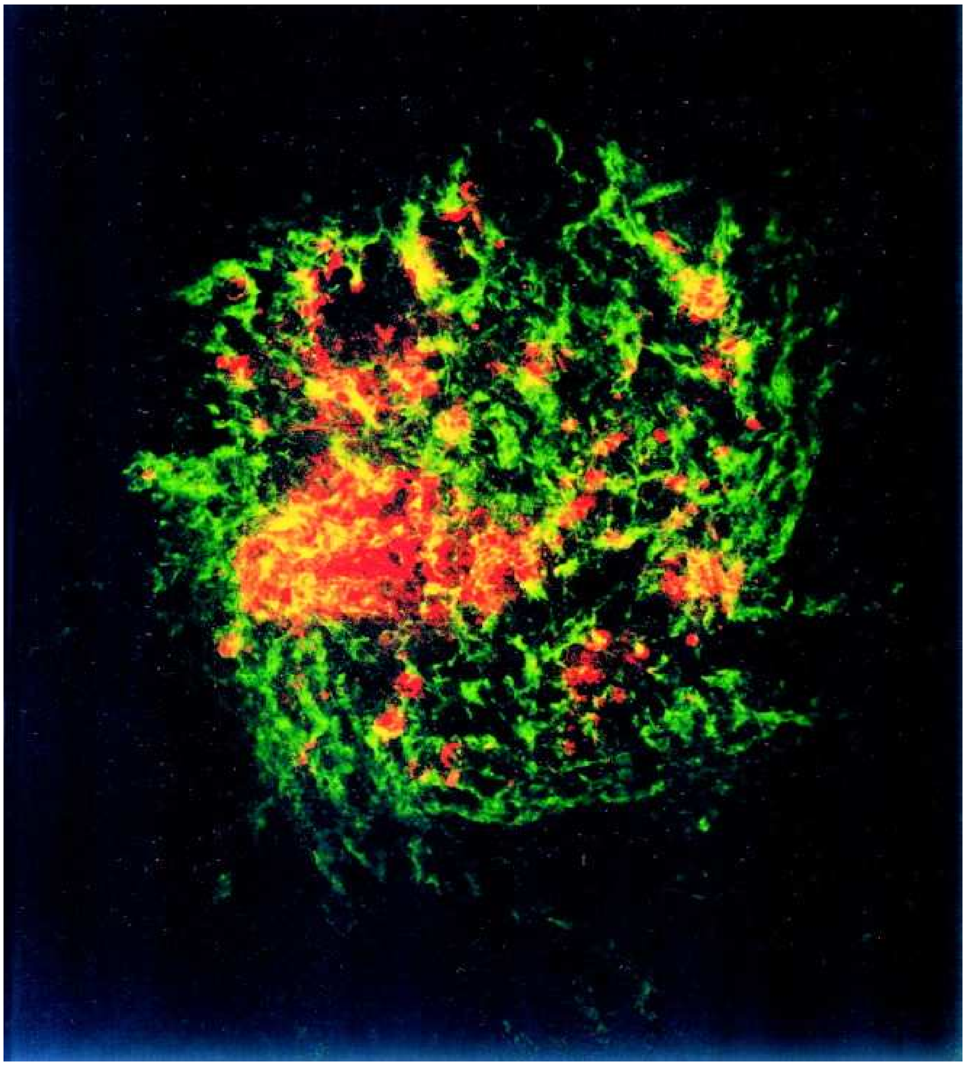

Figure 1. Peak HI surface brightness map by Kim et al. (1999) in green with overlaid an Hα image (with the continuum subtracted) of the LMC in red.

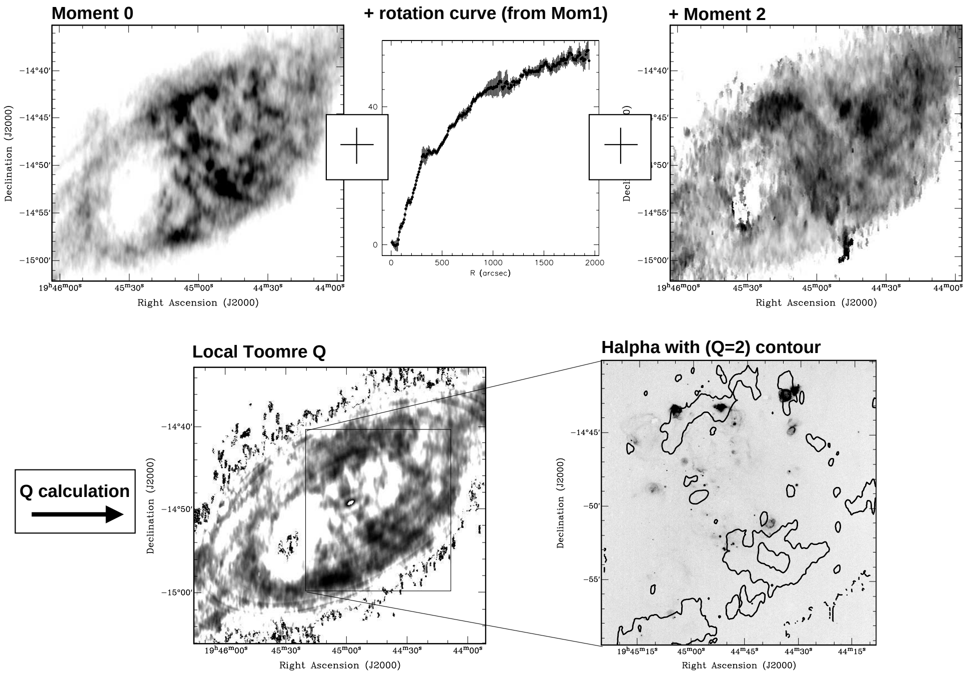

Figure 2. HI surface brightness map based on ATCA observations of the dwarf irregular galaxy NGC 6822 (de Blok & Walter 2000) shown in the top left panel. The high resolution rotation curve is shown in the top middle and is combined with the surface brightness and velocity dispersion maps to produce a “Toomre Q” map (bottom left) at linear scales of 90 pc. Dark regions correspond to low Q, implying that the gas there is gravitationally unstable and will turn molecular, fragment and form stars. An Hα map is shown in the lower right. The SKA will allow the determination of the “Toomre Q” locally and investigate its behavior as a function of environment and galaxy type.

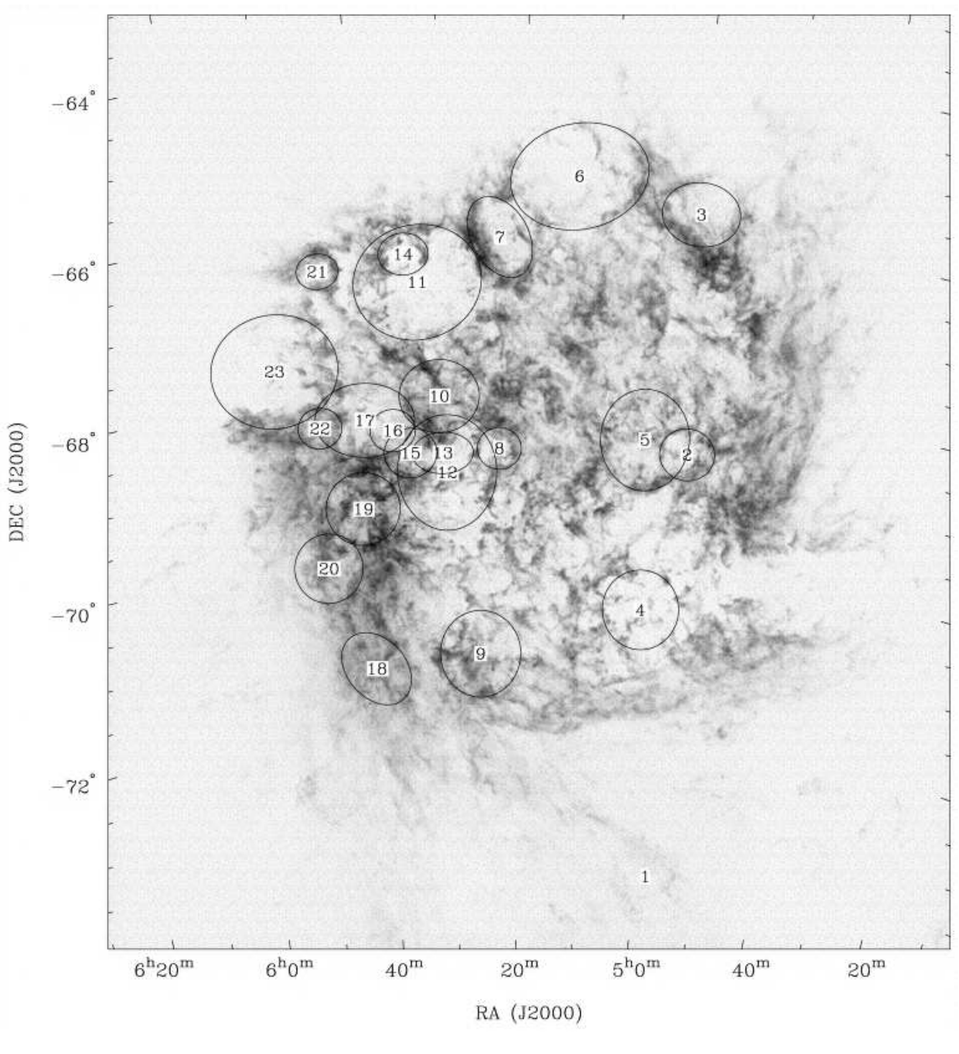

Figure 3. Peak HI surface brightness map for the LMC (Kim et al. 2003). The gray scale intensity range is 0 to 136.7 K. This map is sensitive to the small HI clouds with the highest opacity along the line of sight. In such regions, the brightness temperature will approach the spin temperature of the HI. The image is similar to the ATCA–only image of Kim et al. (1998) and emphasizes the filamentary, bubbly, and flocculent structure of the ISM in the LMC. The locations of supergiant HI shells are indicated.

It is this process which helps maintain the velocity dispersion of the gas at its canonical value of around 6–7 $\mathrm{km\,s^{-1}}$ (at least at scales of several hundred pc) and which has been named as a possible explanation for the High Velocity Clouds or HVCs (Galactic fountain model; Shapiro & Fields 1976; Bregman 1980). The velocity dispersion of the gas largely defines the thickness of the gas disks in gas rich spiral and dwarf galaxies. It has been shown that especially in dwarf irregular galaxies (dIrr) the disks are thicker in relative and absolute sense (Brinks et al. 2002), increasing the probability for lines of sight toward high redshift objects to intersect these halos, giving rise to DLyα lines. Similarly, the hot gas hurled into the halo will eventually cool and condense, augmenting effectively the cross section of a spiral galaxy and providing an explanation for DLyα and associated metal lines. Importantly, dIrr galaxies, which are thought to be particularly abundant at large lookback times in current bottom up scenarios, might not be able to hold on to the expanding material leading to an early enrichment of the IGM (Mac Low & Ferrara 1999; Ferrara & Tolstoy 2000).

The SKA will have a huge impact on this field as it will have the sensitivity and resolution to map extremely low column density gas around nearby galaxies, exploring the origin of HVCs and linking the existence of gas at large distances from a galaxy with recent star formation. The fact that this will come within reach of the SKA is due, in part, to its high surface brightness sensitivity. Opting for a synthesised beam of, say 45″ this corresponds to 800 pc @ 3.6 Mpc and 2.5 kpc @ 10 Mpc; using a channel width of 10 $\mathrm{km\,s^{-1}}$, a 24 hr observation will reach typical column densities of $4 \times 10^{17}\,\mathrm{cm^{-2}}$ which reaches well below the limit where HI is supposedly ionised by the meta–galactic radiation field. If pockets of gas exist which were somewhat denser and more resistant to ionisation, a 1 hr observation with the same beam and velocity resolution corresponds to mass limits of 400 $\mathrm{M_\odot}$ @ 1 Mpc or $4 \times 10^4\,\mathrm{M_\odot}$ @ 10 Mpc.

At these sensitivities (Compact) High Velocity Clouds around external galaxies come within easy reach (de Heij et al. 2002, Thilker et al. 2004) as will be the so called "anomalous" gas which has been found in very deep maps of a few individual galaxies (Schulman et al. 1996, 1997; Fraternali et al. 2002). As mentioned, SKA observations will have the sensitivity and resolution to investigate the link between SF activity (and the aftermath of stellar death) in the disks of galaxies and material in the halo, verifying the validity of the galactic fountain model. Moreover, the SKA will be able to map this low density gas and see if there is any link with gas–rich satellite galaxies orbiting the bigger galaxy and eventually being dragged towards it through dynamical friction.

3. HI in absorption — going to the limit

The SKA will revolutionise HI absorption studies. For HI absorption, the sensitivity is ultimately determined by the flux density of the background source (or in the case of the source being extended, its surface brightness) against which absorption is detected. Assuming a 12 hr integration at 1 $\mathrm{km\,s^{-1}}$ velocity resolution (cold HI clouds will have narrow line widths) one can reach an rms noise of 15 μJy per channel. The SKA will thus be able to detect a 10% absorption feature ($\tau \approx 0.1$) against a 1 mJy background source at better than 6σ signal to noise (or a column density of $2 \times 10^{19}\,\mathrm{cm^{-2}}$ for $\mathrm{T}_{sp} = 100\,\mathrm{K}$ spin temperature gas).

The expected source density of sources brighter than 1 mJy, based on source counts at 20 cm wavelength is $\sim 3 \times 10^5\,\mathrm{sterad^{-1}}$ (Hopkins et al. 1998). There will therefore be of order 100 background sources bright enough for absorption line studies behind M 33, some 500 sources in the field of M 31, and over 3000 behind the LMC. The best one can do currently with instruments like the VLA in the nearest galaxies like M 31 and M 33 is measuring absorption towards a dozen background sources (Braun & Walterbos 1992; Dickey & Brinks 1993). HI absorption measurements against background sources seen through the disks of gas rich galaxies can be used to extract crucial information regarding the spin temperature of the gas, T_{sp}, and the fraction of cool versus warm gas filling the ISM, both globally and as a function of position in a galaxy. This can only be done with the SKA.

HI absorption against extended background sources will reveal fine structure in the ISM, the limit of which is set only by the brightness temperature distribution (angular size) of the background source. Note that for these type of observations one can exploit the full resolution of the SKA. These observations can be linked to efforts by several groups (e.g., Gazol et al. 2001) to gain a theoretical understanding of the 3D and temperature structure of the ISM, involving turbulence. Most studies have been focussing on the Milky Way, understandably. With the SKA similar studies can be extended to other galaxies, notably the LMC/SMC and larger galaxies in the Nearby Universe.

4. Concluding Remarks

The SKA will have a profound impact on HI studies of the Nearby Universe. For the same observing time, the SKA will provide maps at an order of magnitude higher angular resolution, twice the velocity resolution and a factor of perhaps two in improved sensitivity. SKA maps of nearby galaxies will provide the benchmark against which high redshift studies will be evaluated. The SKA will tackle such fundamental questions as what triggers star formation at the scale of neutral atomic clouds ($\sim$ 100 pc) and what is the relation between violent star formation, and the death of massive stars, and the neutral gas which is seen at low column densities in the haloes of spiral galaxies. Is this gas due to outflow or are we rather seeing infall of gas, either stripped material from satellite galaxies which are in the process of merging, or primordial material which is still accreting. Lastly, HI absorption line studies will finally reveal what fraction of the ISM is in the form of cool ($T_{sp} = 80$ K) versus warm ($T_{sp} = 8000$ K) gas, addressing the validity of the fundamental and possibly erroneous assumption of the HI gas being optically thin.

REFERENCES

1. Braun, R. & Walterbos, R. A. M. 1992, ApJ, 386, 120
2. Bregman, J. N. 1980, ApJ, 236, 577
3. Brinks, E. & Bajaja, E. 1986, A&A, 169, 14
4. Brinks, E., Walter, F. & Ott, J. 2002, in Disks of Galaxies: Kinematics, Dynamics and Perturbations, eds. E. Athanassoula, A. Bosma, and R. Mújica, ASP Conf. Proc. 275, p. 57
5. de Blok, W. J. G. & Walter, F. 2000, ApJ, 537, L95
6. de Heij, Braun, R. & Burton, W. B. 2002, A&A, 392, 417
7. Dickey, J. M. & Brinks, E. 1993, ApJ, 405, 153
8. Ferrara, A & Tolstoy, E. 2000, MNRAS, 313, 291
9. Fraternali, F., van Moorsel, G., Sancisi, R. & Oosterloo, T. 2002, AJ, 123, 3124
10. Gazol, A., Vázquez–Semadeni, E., Sánchez–Salcedo, F. J. & Scalo, J. 2001, ApJ, 557, L121
11. Hopkins, A. M., Mobasher, B., Cram, L & Rowan–Robinson, M. 1998, MNRAS, 296, 839
12. Kennicutt, R. C., Jr. 1989, ApJ, 344, 685
13. Kennicutt, R. C., Jr. et al. 2003, PASP, 115, 928
14. Kim, S., Staveley–Smith, L., Dopita, M. A., Sault, R. J., Freeman, K. C., Lee, Y., & Chu, Y.–H. 2003, ApJS, 148, 473
15. Kim, S., Dopita, M. A., Staveley–Smith, L., & Bessell, M. S. 1999, AJ, 118, 2797
16. Mac Low, M–M. & Ferrara, A. 1999, ApJ, 513, 142
17. Martin, C. L. & Kennicutt, R. C. 2001, ApJ, 555, 301
18. Schulman, E., Brinks, E. , Bregman, J. N. & Roberts, M.S. 1997, AJ, 113, 1559
19. Schulman, E., Bregman, J. N., Brinks, E. & Roberts, M.S. 1996, AJ, 112, 960
20. Shapiro, P. R. & Fields, G. B. 1976, ApJ 205, 762
21. Thilker, D. A., Braun, R., Walterbos, R. A. M., Corbelli, E., Lockman, F. J., Murphy, E. & Maddalena, R. 2000, ApJ, 601, L39
22. Walter, F., Brinks, E., de Blok, W. J. G., Thornley, M. & Kennicutt, R. 2004, BAAS, 204 (submitted)