

Spectral line mapping of the Milky Way

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Abstract

SKA will give the opportunity to map our Galaxy in thermal lines of HI, OH, and recombination lines, tracing all three phases of the gas content of the Galaxy (atomic, molecular and ionized hydrogen) with the same angular resolution. These studies would deliver a comprehensive spatial and kinematical view of the interstellar medium, its evolution, and the interrelationship between its phases. Moreover, observations of OH maser emission will provide us with a complete catalog of sources undergoing energetic mass loss, covering star-forming regions and evolved stars, and with detailed information about their internal motions and the strength of their magnetic fields.

1 Mapping our Galaxy

Understanding our own Galaxy is obviously of great importance. Our location within it gives us certain observational advantages, but also imposes some restrictions and challenges. The most favorable aspect is that we can study the spatial and kinematical characteristics of different structures with far better detail than in any other external galaxy. This means that we can directly observe the interplay between different phases of the interstellar medium, as well as feedback between the gas dynamics and key physical processes such as mass-loss from young and evolved stars. In summary, it is possible to study evolutionary processes in our Galaxy and then use this detailed knowledge to understand Galactic evolution in other galaxies, where many of these physical phenomena are not accessible.

Spectral line studies are key in our knowledge of the general Galactic structure, as well as in the study of star formation and the last stages of stellar evolution. This is mainly because these lines provide information on the gas kinematics (determined by their Doppler shifts) and on its temperature and column densities. The line of atomic hydrogen (HI) at 1.4 GHz [12] has been instrumental to determine the structure of the spiral arms in the Galaxy, and the location of the Solar System in our Galaxy. The millimeter CO lines, as well as a plethora of other molecular lines at different wavelengths (such as CS, NH₃, SiO, and NH₂⁺)

are good tracers of molecular gas (under different density and excitation conditions), and have provided fundamental insights in the processes of star formation [21]. On the other hand, maser emission from different molecules (OH, SiO, CH₃OH, H₂O) are useful signposts of energetic phenomena in the circumstellar environments of young and evolved stars [9].

Specific aspects of the study of molecular lines in star-forming regions and evolved stars with SKA are treated elsewhere in this document. Here we will focus on some of the information that we can obtain by carrying out a large-scale mapping of our Galaxy in spectral lines. Considering the frequency coverage of SKA1, the most relevant spectral lines for such a mapping are the 1.4 GHz line of HI, and the ground-state OH lines at 1.6 – 1.7 GHz. Thermal emission from OH is a tracer of diffuse molecular gas, while OH maser emission traces energetic processes with extremely high spatial accuracy. Other interesting lines are the maser transitions of methanol (e.g., 6.7 and 12.1 GHz) and excited OH (4.7, 6.0, 13 GHz).

This mapping of spectral lines in our Galaxy is challenging in several aspects. First, Galactic emission covers a large fraction of the sky. For instance, a mapping of Galactic latitudes $|b| < 3^\circ$ of the plane south of declination 40° would cover $\simeq 1500$ square degrees. For such a huge area it is not enough to be able to make observations with high sensitivity. It is also necessary to do so fast enough to cover the whole Galactic emission in a reasonable time. Therefore the relevant figure of merit in Galactic mapping is not sensitivity, but “survey speed”, i.e., how fast one can map a large area of the sky at a given sensitivity level, and it is governed by the immediate field of view, in addition to the collecting area. Survey speed will be one of the strongest points of SKA1. For instance, SKA1-mid will have a survey speed around two orders of magnitude higher than the Very Large Array in its A configuration. This means that a mapping of the Southern Galactic plane with high sensitivity and angular resolution will be feasible in reasonable integration times with SKA. Note also that the field of view of the SKA will be smaller as we move to higher frequencies, so a large-scale mapping of the Galaxy is more efficient at lower frequencies. This, and the possibility of simultaneously observing several lines (see section 2), suggest that spectroscopic surveys of our Galaxy should first focus on the lines around 1.4-1.7 GHz, for which the field of view will be $\simeq 0.49$ square degrees (a mapping of the southern Milky Way with $|b| < 3^\circ$ and $\text{dec} < 40^\circ$ requires $\simeq 3000$ individual pointings). Other lines at higher frequencies would be better observed commensally with radio continuum surveys, in a similar way as the MeerGal survey will do at $\simeq 14$ GHz using MeerKat [29].

An additional challenge when carrying out a spectral line mapping of our Galaxy is not only that the total size to be covered is large, but also that there are relevant structures at different scales, from several degrees down to the resolution limit of the telescope. However, interferometers have a limit to the largest angular scale they can sample, determined by the length of its shorter baseline. Although SKA will probably be designed to minimize such losses, this is an inherent limit that cannot be completely avoided. A complete picture of the Galaxy will require the combination of SKA data with data from single-dish telescopes, such as the Parkes Galactic All-Sky Survey (GASS [17], Fig. 1) in HI and the Southern Parkes Large-Area Survey in Hydroxyl (SPLASH [6] in OH), so that we can properly sample both large and small scales. An important step forward will be provided by the Galactic ASKAP Survey (GASKAP [8]), which will map our Galaxy in HI and OH with the Australian Square

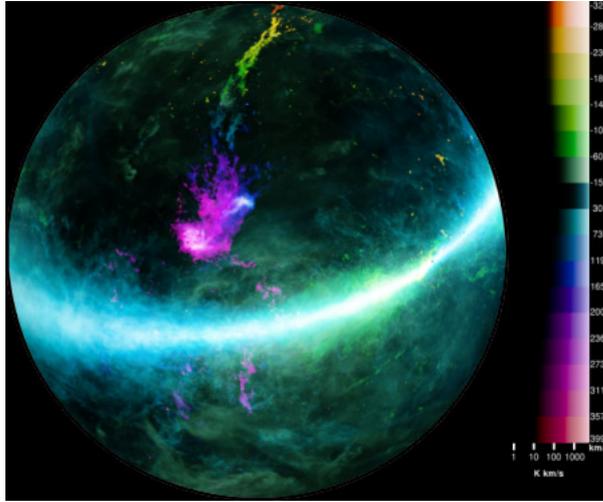


Figure 1: Map of the HII emission obtained with the Parkes antenna for the GASS project (image from [17]). The South Celestial Pole is at the center. Right ascension zero is at the top and it increases counter-clockwise. Different colors represents the velocity with respect to the Local Standard of Rest, in intervals of 40 km s^{-1} . The color intensity is proportional to the integrated brightness temperature over each velocity interval.

Kilometre Array Pathfinder with $10'' - 20''$ angular resolution. SKA will add another piece to the puzzle, to increase the detail and sensitivity provided by previous spectral line surveys.

2 Thermal lines: the three phases of the interstellar medium

SKA1 will allow us to study thermal spectral lines from the three phases in which the gas can be found in the interstellar medium. In particular, the HI line at 1.4 GHz emitted by the atomic component, four OH transitions at 1.612, 1.665, 1.667, and 1.720 GHz tracing molecular gas, and several recombination lines of hydrogen and helium around those frequencies (e.g, $Hn\alpha$, with n between 155 and 163) for the ionized phase. The rest frequencies of all these lines are within $\simeq 400 \text{ MHz}$, so it will certainly be possible to observe them simultaneously with the appropriate correlator setup and *with the same angular resolution*, which would be an extremely efficient way to carry out studies of the physical conditions and evolution of the interstellar medium in our Galaxy. In a single pass we will have a picture of the whole mass content of the Galaxy and with unprecedented detail. The angular resolution of SKA1-mid at these frequencies ($0.22''$) would correspond to a linear scale of only $\simeq 1800 \text{ AU}$ at the distance of the Galactic Center, so we could reach circumstellar scales.

A spectral line mapping of our Galaxy will give valuable information on each of the phases of the interstellar medium. For instance, recombination lines from ionized gas will provide a complete census of regions of massive star formation and planetary nebulae, even at the farthest reaches of the Galaxy, without being affected by interstellar extinction, and

including kinematical information of each system in its Galactic motion and in its internal outflows. However, even more important will be the availability of a coherent picture of all phases of the interstellar medium, to study their interrelationship. This includes answering questions on how the atomic gas evolves into molecular gas, creating the molecular clouds from which new stars will form. The energy input from young stars will create winds and photoionized (HII) regions that will influence the subsequent generation of stars. At the end of the stellar life cycle, planetary nebulae and supernovae will send material back to the interstellar medium, enriching it with heavier elements.

By combining data from SKA1 and sensitive single-dish surveys, we will have access to the whole hierarchy of scales. Starting from the kpc scales (flocculent spiral arms and gas supercomplexes), new structures and substructures could arise [16], indicating how spiral arms drive processes down to smaller scales. The largest hierarchical scales of gas with coherent velocity patterns are relevant, since the largest complexes of coherent HI gas can be related to how star formation will proceed, and to what extent it can be triggered by large-scale Galactic processes and turbulence [10]. Down in the hierarchical ladder, we find shell and chimneys created by stellar winds and supernovae (at scales of 10-100 pc), direct witnesses of the energy exchange between stars and the interstellar medium [3]. Smaller structures (< 1 pc) can be created by instabilities in shell walls [5] or in turbulent flows [32]. Some of these smallest structures can evolve into molecular clouds with induced star formation.

The comparison between HI and OH will give us the fraction of molecular gas (with respect to total gas) in the whole galaxy, with an unsurpassed angular resolution. This fraction is thought to depend on pressure, metallicity, and ultraviolet radiation [11]. The detailed variation of the fraction of molecular gas with galactocentric distance and height above the plane will give us information about the physical processes acting at different locations and about the history of star formation in our Galaxy. Sampling multiple scales will allow us to study the characteristics of turbulence, by studying the fractal structure of atomic and molecular clouds [24], or the relationship between the velocity distribution and the mass and size of clouds [15] or of clumps within clouds. By doing this in a complete sample of clouds, we could see how turbulence evolves, and whether there are particular cloud characteristics that will determine the subsequent process of star formation.

At high Galactic latitudes, we can obtain a full count of high-velocity clouds in the galactic halo [33], together with their detailed structural and kinematical characterization. This could reveal the origin of these clouds (which is still uncertain), how they interact with both the halo and the Galactic disk along their path of motion, and whether they are a significant source of mass input into the Galactic disk, which would in its turn determine the star formation rate in our Galaxy.

Diffuse HI and OH emission does not have a high brightness temperature. Therefore, its mapping at the full angular resolution of SKA1 would in principle require prohibitively long integration times. However, the antenna configuration of SKA1-mid is centrally condensed, so the visibilities can be tapered (downweighting the longest baselines) without losing much overall (point-source) sensitivity. If we set a target sensitivity in terms of brightness temperature, increasing the integration time per field would then allow us to improve the angular resolution of the final maps. As a benchmark, a dwell time of 1 hour per field with SKA1-mid

would already provide maps with the same sensitivity as those in the low-latitude component ($|b| < 2.75^\circ$) of the GASKAP survey at $20''$ angular resolution (dwell time of 50 hours), but with a factor of two better angular resolution ($10''$). Such a mapping would require a total of $\simeq 2800$ hours of SKA1-mid time. Subsequent visits over the lifetime of the instrument would then allow obtaining maps with increasingly higher final angular resolution.

3 Maser emission: signposts of energetic processes

Maser emission requires a very energetic process (either shocks or intense radiation fields), so that the population between two energy levels of an atom or molecule is “inverted” (i.e., the upper level is overpopulated over a thermal situation). Background photons with the energy corresponding to the energy difference between these states rapidly stimulate the energy decay. The result is a bright, and usually compact (< 1 AU) emission.

At the frequencies covered by SKA1, the most widespread maser lines are those of the ground state of the OH molecule at 1612, 1665, 1667, and 1720 MHz. Although different types of sources can emit in all these transitions, there are some identifiable trends. The satellite line at 1612 MHz is dominant in the circumstellar envelopes of oxygen-rich evolved stars, especially those in the Asymptotic Giant Branch (AGB) that show characteristic double-peaked OH maser spectra with peak separations of $\simeq 30$ km s $^{-1}$ [26]. The main-line transitions at 1665 and 1667 MHz are prominent in regions of massive star formation [2]. The presence of the 1720 MHz line alone is usually associated to shocks at the interactions of supernova remnants with molecular clouds [13]. Thus, the relative intensities of OH transitions are useful to discriminate among young and evolved objects.

Maser spots will appear as point sources with the angular resolution of SKA1. Therefore, observations will not suffer from any loss of extended emission and no complement from single-dish data will be needed. Moreover, maps can be obtained at the full angular resolution provided by the antenna configuration, while retaining the maximum signal-to-noise ratio. We also note that, if there is a velocity gradient in a source, different spots of maser emission will appear in separate spectral channels. This allow us to measure spatial and kinematical structures at scales much smaller than the resolving power of the telescope, since the relative positional accuracy within two point sources in a map [19] is given by $\sigma = \theta / (2 * sn)$, where θ is the synthesized beam, and sn is the signal to noise ratio of the emission. The sensitivity of SKA will be the key factor in improving this relative positional accuracy. As an example, this accuracy is $\simeq 0.15$ milliarcsec for maser emission at a level of 0.5 Jy with SKA1-mid with only one hour of observing time and a velocity resolution of 0.2 km s $^{-1}$.

Another useful aspect of OH emission is that its levels undergo Zeeman splitting in the presence of a magnetic field [1] (see chapter by Girart in this book). Thus, it is straightforward to measure circular polarization with these lines, which is related with the magnetic field strength along the line of sight. In sources where internal Faraday rotation does not have a strong effect, the orientation of the linear polarization vectors [14], and the degree of linear polarization can give us information about the overall spatial orientation of the field.

SKA1-mid will have enough sensitivity to detect almost all OH masers in our Galaxy

with just 45 minutes per field of view, assuming that their typical luminosity is similar to those detected near the Galactic center [28]. So we will obtain a complete catalog of Galactic OH masers, including a detailed measurement of the spatio-kinematical structure within each source, and the strength and orientation of their magnetic field (in $\simeq 2300$ hours, to cover $|b| < 3^\circ$). This will be a powerful tool when compared with large scale surveys at other wavelengths, since we can obtain statistically significant correlations about different physical properties both in young and old stars. Moreover, the high sensitivity of SKA could unveil a new population of weaker OH masers, pumped in circumstellar environments different from those we now know. Even known OH-emitting objects could reveal a wealth of weaker maser components, tracing kinematics and magnetic fields over a more extended region. These observations will also uncover the whole catalog of some particularly interesting OH-emitting evolved objects, of which very few members are known so far, such as post-AGB stars undergoing collimated mass loss [7] or extremely young planetary nebulae [31]. In the case of star-forming regions, OH masers in star-forming regions, not directly associated with ultracompact HII regions, can pinpoint the location of high-mass protostars, in their very first stages of evolution.

The structures traced by OH masers show a significant diversity. In particular, these masers can be found in jets, circumstellar disks, or in uncollimated winds, and this is the case both in young and evolved objects [22, 4]. A sensitive OH survey in our Galaxy would allow us to determine the relative incidence of these different structures, and under what conditions either is produced. It is possible that this is an evolutionary effect, and the structure traced by OH masers will depend on the relative age of the object. A complete morphological catalog of OH masers in our Galaxy can give us a better understanding of the processes leading to the formation and death of stars, since the presence of disks and collimated outflows are key ingredients in models of star formation via accretion [27] and to explain the shaping of planetary nebulae [23]. However, the earliest phases of massive star formation may be characterized by short episodes of uncollimated mass-loss [30]

Previous studies of Zeeman splitting of OH masers suggest that the orientation of the field traced by this emission may be consistent with that found at larger scales in our Galaxy [20]. This persistence after collapse in molecular clouds is surprising, since masers trace scales and densities that differ several orders of magnitudes from those of the diffuse interstellar medium. With a large and unbiased data base of Zeeman splitting of OH masers in star-forming regions we can make a more precise comparison with the Galactic magnetic field [18]. In evolved stars, we could study the evolution of magnetic fields, and whether there is any correlation between their strength and orientation with the degree of collimation observed in post-AGBs and PNe.

The radial velocities of OH masers can also be used to study Galactic dynamics [25]. Specially in the case of AGB stars, whose OH maser spectra typically consist of two well-defined peaks, the radial velocity of the system is very easy to obtain (it is just the mean velocity between the peaks). Thus, we will have a perspective of Galactic dynamics from the population of these old stars, which can be compared with that provided by the gaseous component (from thermal HI and OH emission) or from different stellar populations sampled in the optical by GAIA.

Acknowledgments

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