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THE GALACTIC INTERSTELLAR MEDIUM IN THE RADIO: PROSPECTS FOR THE SKA

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Abstract. The upcoming Square Kilometre Array (SKA) promises incredible advances across many areas of astrophysics: from the epoch of reionisation, galaxy evolution, and cosmology, to nearby galaxies, the Milky Way and the Sun. In particular, the wide variety of observations (spectral, continuum, polarisation, multi-scale, wide-band) enabled by the SKA, will allow us to perform new and exciting studies of the interstellar medium (ISM) of our own Galaxy. These cover the multiphase medium, mass flow in and out the Galaxy, magnetic fields, the formation of molecular clouds, tomography, down to the evolution of dust grains and molecular complexity. Such studies are well represented in the French SKA White Book, which demonstrates the broad expertise of the French ISM community and therefore the important role that it has to play in the SKA project.

The aim of this article is to illustrate the prospects offered by the SKA for ISM studies by summarising the contributions in the Galactic Astronomy chapter of the French SKA White Book: `http://adsabs.harvard.edu/abs/2017arXiv171206950A`.

Keywords: ISM: general, Astronomical instrumentation, methods and techniques

1 The SKA project and the French effort

The Square Kilometre Array (SKA) is an international project whose aim is to build the largest radio telescope, which, when complete will reach one square kilometre of collecting area - as its name indicates. The telescope will be built on two sites: one in Western Australia and one in South Africa. The Australian site, in the Murchison desert, will host the low-frequency array (SKA-LOW), which will be made up of hundreds of thousands of simple antenna elements organised in stations of a few meter diameter. These will be separated by a few tens of meters up to hundreds of kilometres. The African site will host the mid-frequency array (SKA-MID), which will consist of hundreds of 15 m dishes. The dishes will be initially distributed in the Karoo desert and will later on extend to different states in central-northern Africa, attaining baselines of hundreds to thousands of kilometres. There is an additional important site in the project, Jodrell Bank in the UK, as it hosts the SKA headquarters. The first phase of the project, also called SKA1, corresponds to about 10 % of the full final instrument and its construction is planned to begin in 2019, with the first science operations starting in the early 2020's. Developments towards the full SKA are planned to start after 2025. SKA1-LOW will cover the frequency range 50–350 MHz, with about 131000 antennas having a maximum baseline of around 65 km. Compared to the LOw Frequency ARray (LOFAR), the current best similar instrument in the world, SKA1-LOW will have 25 % better angular resolution, it will be 8 times more sensitive and have 135 times its survey speed. SKA1-MID will observe between 350 MHz and 15.5 GHz (possibly up to 30 GHz in the final phase), with 133 15 m diameter dishes in addition to the 64 MeerKAT antennas already in place, separated by 150 km at maximum. Compared to the Jansky Very Large Array (JVLA), the current best similar instrument in the world, SKA1-MID will have 4 times better angular resolution, it will be 5 times more sensitive and have 60 times its survey speed.

[*]Thanks to the French ISM community

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The main science driver of the SKA, which dates back to the early 90's when the original conception of the project appeared, is an accurate and precise measurement of the 21 cm emission from neutral hydrogen (HI) at cosmological distances. Such observations will allow us to measure the HI content of galaxies up to 5–6 Gyr back compared to the $\sim$ 2–2.5 Gyr achieved with today's telescopes. In addition, mapping of the HI across cosmic time is a unique tool to study the cosmic dawn and the epoch of reionisation, two phases of the Universe starting at around 100 and 280 Myr after the Big Bang, respectively. Other major scientific cases, which can only be explored with the SKA, are the study of pulsars and of cosmic magnetic fields. The radio emission from pulsars will allow us to study the extreme physics that these objects enclose and furthermore, perturbations in pulsar distances will be used to probe gravitational waves, which is a truly exciting prospect especially after the recent direct detection by the LIGO and VIRGO collaborations. The SKA will measure Faraday rotation acting on polarised synchrotron emission, from background radio sources (galaxies, pulsars) and from the diffuse galactic medium itself, which will enable the study of magnetic fields in various kinds of sources and on a range of spatial scales that has not yet been explored (few million kilometres, e.g. in heliospheric coronal mass ejections, to tens of megaparsecs, e.g. in cosmic filaments and galaxy clusters). Given the exceptional characteristics of the SKA, this project will lead to major advances in many other areas in astrophysics. Different science working groups (SWG) have been identified; their list can be found here: `https://www.skatelescope.org/science/`. For further details on the goals of each SWG we refer to the proceedings of the meeting "Advancing Astrophysics with the Square Kilometre Array"*.

The last few years have seen an increasing activity of the French astronomy community as well as large industrial groups around the SKA project, owing to the major scientific breakthroughs that it will enable, but also for the technical challenges that its construction and maintenance involve. These various activities, which were largely organised by the "Maison SKA France"†, have culminated in a few first big successes: the publication of the French SKA White Book in 2017, the addition of the SKA in the French roadmap of large research infrastructures (*TGIR*) in 2018, and the recent entry of the Maison SKA France in the SKA Organisation. The French SKA White Book includes the contributions of 176 authors from 40 research laboratories and puts together six scientific chapters, which broadly cover the whole range of science enabled by the SKA. The Galactic Astronomy chapter, relevant to ISM studies addressed in this article, was written by 40 scientists from 12 different institutes and contains 11 sections in a variety of topics. Studies of the Galactic ISM with the SKA pertain to the following SWGs: Our Galaxy, Cosmic magnetism, and Cradle of life/Astrobiology. All of the eleven SKA SWGs have French participants; out of the 46 French researchers involved in the different SKA SWGs, 12 are part of the aforementioned ISM-related groups.‡

2 ISM studies with the SKA

This section will start with a brief introduction to the ISM of galaxies, followed by the motivation to use the SKA to study the ISM of our Galaxy, and will then present a summary of the different ISM studies proposed by the French community.

2.1 The ISM of galaxies

The ISM of galaxies is everything that lies in between the stars. It is composed of dust and gas, commonly referred to as interstellar matter, magnetic fields, and cosmic rays. The ISM is typically divided into three phases according to the dominant state of the gas: molecular, atomic, and ionised. Studying the physical properties of the different phases as well as how they evolve and connect to each other is crucial to understand the evolution of the ISM as a whole. But in order to do so, one has to consider the interaction between the stars and the ISM, which is undoubtedly the key factor determining its evolution. In a nutshell, stars form by gravitational collapse in the densest parts of the ISM, i.e. the molecular clouds, and these in turn form from the diffuse medium. Once stars are born, they interact with the surrounding medium in different forms: they heat and ionise the ISM, they enrich it with new heavier material, they change its structure through what is called stellar feedback. In particular, feedback from massive stars in the form of stellar winds, formation of ionised

*`https://pos.sissa.it/cgi-bin/reader/conf.cgi?confid=215`

†`https://ska-france.oca.eu/fr/accueil-ska`

‡Source (regularly updated): `https://astronomers.skatelescope.org/science-working-groups/`. We remind that all SWGs are open to self-nominations from prospective members who do not have to reside in a SKA member country. All researchers working in a relevant field of astrophysics are encouraged to apply.

(HII) regions or supernova explosions, represents the main source of energy injection into the ISM, some of it in the form of turbulence (i.e. kinetic energy). In turn, turbulent motions along with the action of magnetic fields can lead to the formation of new density and temperature variations in the ISM, which may evolve into forming dense and cold molecular regions where gravity will take over and lead to the formation of another generation of stars. For a complete reading we refer to, e.g., Ferrière (2001), Tielens (2005), and Draine (2011).

Although we understand rather well many of the processes involved in the cycle described above, there are still several open questions, which we can address with the SKA. Some of them are discussed in this article.

2.2 The SKA: a unique machine to study the Galactic ISM

There are several reasons why the SKA will be a unique instrument to study the Galactic ISM. First, the SKA will probe all of the ISM constituents: interstellar matter, magnetic fields, and cosmic rays. Second, owing to the large frequency coverage (50 MHz to 15.5 GHz, possibly 30 GHz), which encompasses several different tracers, and the spectral and polarimetric capabilities, we will be able to study the three phases of the ISM. Third, the high resolution, which will go from a fraction of an arcsecond at low frequencies down to about 30 milliarcseconds at the highest frequencies, will allow us to study small-scale objects such as disks, filaments, shocked and dissipative structures. Finally, the high sensitivity combined with a large mapping speed will enable us to investigate the multi-scale and multi-phase physics of the ISM. The molecular gas will be traced with hydroxide (OH) emission as well as with absorption by e.g. formaldehyde (H_2CO); the neutral gas with, naturally, the HI line both in emission and absorption; the ionised gas will be probed using its continuum bremsstrahlung (free-free) emission as well as hundreds of recombination lines and dispersion measures of Galactic pulsars; dust properties will be investigated using the so-called anomalous microwave emission as well as continuum dust emission measured at the highest frequencies. Several different complex organic molecules (COMs) are also included in the SKA band, especially at the highest frequencies. Interstellar magnetic fields will be studied using Zeeman effect measurements, rotation measure (RM) observations, as well as Faraday tomography. Synchrotron emission, strongest at low frequencies, is the tracer of both cosmic rays and magnetic fields.

In order to illustrate the potential of the SKA for ISM studies, we will now summarise the content of the eleven Galactic Astronomy sections of the French SKA White Book.

The nearby interstellar medium : With the SKA we will be able to study the nearby ISM in exquisite detail and, for the first time, with homogeneous coverage in angular resolution of the three ISM phases. The SKA will in particular improve our 3D view of the nearby ISM. For instance, by combining HI observations with 3D maps of dust density derived from stellar data (Marshall et al. 2006; Green et al. 2014; Lallement et al. 2014), notably from Gaia, we will obtain the distribution of the gas in 4D phase space. In addition, SKA1-MID will be an excellent complement to stellar missions as it will provide accurate astrometry to stars obscured by clouds that Gaia cannot detect. Models of the 3D distribution of the ionised gas, i.e. of the free electron density (e.g. Cordes & Lazio 2003), will also be largely improved by combining observations of recombination lines, free-free continuum emission, and pulsar dispersion measures. The latter will be particularly important to map the density distribution in the nearby medium. Overall, such a detailed knowledge of the gas distribution will help us trace the origin and the flow of matter from the halo through the ISM, where its collapses and feeds star formation.

Turbulent cascade: Interstellar turbulence is usually described as a self-similar cascade of energy from large scales ($0.1 - 1$ kpc), at which energy is injected by supernovae and Galactic shear, to small scales (10^{-5} pc), at which energy is dissipated (e.g. Kolmogorov 1941). Turbulence is also compressible, intermittent, magnetised, as indicated by several different observations and explained by different theories. However, we still lack a theory capable of describing all the known characteristics of turbulence. The SKA's prime tracer of turbulence will be the HI line. By measuring this line across the sky at unprecedented brightness sensitivity, we will be able to probe the turbulent cascade through fluctuations in atomic hydrogen density across a large range of scales, ~ 1 kpc to 10^{-4} pc (Staveley-Smith & Oosterloo 2015). Smaller scales will be reached with HI absorption measurements, which will constrain turbulence dissipation mechanisms in the neutral ISM (Dickey et al. 2004). HI absorption, as well as carbon recombination lines, can be used to isolate the cold neutral medium (CNM) from the warm neutral medium (WNM), both traced by HI emission. We will thus be able to compare turbulent motions in different ISM phases. In addition, polarisation observations will help probe turbulence in the magneto-ionic medium, e.g. by polarisation gradients of synchrotron emission (Gaensler et al. 2011).

The formation of cold atomic structures: Cold atomic interstellar (or CNM) clouds, in which hydrogen is mostly molecular and in which stars form, are formed from the diffuse and warm atomic medium (the WNM) through a process called thermal instability (Field 1965). However, how exactly this transition occurs is still not fully understood, despite its importance in the regulation of star formation in galaxies (Ostriker et al. 2010). In order to investigate this phase transition and to link it to the star formation cycle, one needs to estimate the amount and the properties of the gas in atomic, molecular, and unstable forms. The SKA will deliver around 2×10^5 HI absorption measures towards radio sources (McClure-Griffiths et al. 2015) (compared to the few hundred currently existing), which will allow the separation between the WNM and CNM and the estimation of, for instance, the CNM fraction in the ISM. This fraction, currently poorly constrained, is theoretically expected to scale with the pressure of the WNM, similarly to the star formation rate (Saury et al. 2014). Observations of HI emission and self-absorption by cold gas in front of a warmer HI background will allow us to map the structure of the cold, warm and thermally unstable gas and to estimate their properties, in and around molecular clouds. Since these observations will cover a large range of physical conditions, we will be able to estimate the timescales of the formation of thermally unstable gas.

Molecular complexity in hot cores and hot corinos: The SKA will open a new spectral range for the study of COMs, currently most explored in the sub-millimetre range (e.g. Caux et al. 2011; Vastel et al. 2016). Some COMs are though to be central species in the synthesis of metabolic and genetic molecules (Saladino 2012), which are the basis of life. In particular, the race to detect glycine in the ISM is on; this molecule is one of the simplest amino-acids and has only been detected in a comet (Altwegg et al. 2016). Despite the unprecedented spatial resolution and sensitivity of the SKA, the detection of glycine will remain very challenging, even in prestellar cores where line blending and confusion is less problematic. The strongest glycine lines are expected at around 20 GHz. If we were to use SKA1 antennas at this frequency, we would need 1000h of integration to detect glycine in a prestellar core like L1544 (estimations made with CASSIS[§]). The situation may improve with SKA2. Nevertheless, SKA1-MID will detect low energy levels of numerous COMs, such as cyanopolyynes, in a very short integration time (less than a minute) in prestellar cores and hot corinos. These COMs are probes of the physical and chemical conditions of the regions.

Interstellar dust: Knowledge of the properties of interstellar dust grains is important not only to understand how they evolve from phase to phase, but also because dust plays a crucial role in many physical and chemical processed taking place in the ISM. With the SKA we will be able to study dust via anomalous microwave emission (AME) and dust continuum emission - especially at high frequencies (> 20 GHz). AME is thought to be electric dipole radiation from rapidly spinning ultra-small grains (Draine & Lazarian 1998; Ysard & Verstraete 2010), but this is still an open question largely due to the limited angular resolution of current instruments that hinder the correlation of AME and possible carriers. The SKA will allow us to clarify this question by observing dense clouds at a few arcseconds resolution. When combined with sub-millimetre and infrared data, the SKA observations will provide the full spectral energy distribution of AME and confirmation of its origin. AME may also be detected in protoplanetary disks with the SKA. This is a particularly novel topic as recent observations suggest that AME in these sources would be due to hydrogenated nano-diamonds (Greaves et al. 2018). In protoplanetary disks, observations of dust emission will help constrain models of grain growth and also to estimate the timescales for the formation of the rocky cores of planets.

Faraday tomography: The new observational technique of Faraday tomography is opening a new window in the study of the Galactic magnetic field. This technique is revealing a rich network of magnetised interstellar structures, in particular of filamentary shape, which are not detected with the traditional ISM tracers. Faraday tomography is particularly powerful as it gives access to line-of-sight information on the magnetised ISM. In a nutshell, by mapping the synchrotron polarised intensity at many different wavelengths in the radio domain and converting its variation with wavelength (due to Faraday rotation) into a variation with Faraday depth, one obtains a so-called Faraday depth cube (Brentjens & de Bruyn 2005). Spectacular results have been obtained with recent LOFAR observations by, e.g. Jelić et al. (2015) and Van Eck et al. (2017). Owing to LOFAR's frequency coverage we are mostly sensitive to nearby structures, i.e. within a few hundreds of parsec. With the much broader frequency coverage of SKA1-LOW, we will observe the nearby ISM at a finer resolution in Faraday depth, in addition to the higher angular resolution. Moreover, with SKA1-MID we will be able to go deeper in Faraday depth space, hence to explore a larger volume of the ISM as well as the internal structure of individual objects like supernova remnants.

Magnetic fields in star formation regions - Zeeman effect of RRLs: Zeeman splitting observations are very valuable to assess the role of magnetic fields in the ISM and in particular in star formation, as they

[§]`http://cassis.irap.omp.eu/`

are the only way to directly measure the strength of the magnetic field in interstellar clouds. Despite their importance, Zeeman measurements are still sparse, mostly because they are time-consuming and often hindered by instrumental effects. The SKA will bring a new burst into these studies as it will allow us to measure, in a significantly smaller fraction of time, the Zeeman splitting of HI, in emission and absorption, of OH (Robishaw et al. 2015), but also, potentially of hydrogen and carbon radio recombination lines (RRLs). The later are particularly useful to trace magnetic fields in star formation regions: H RRLs sample the HII region whereas C RRLs sample the surrounding layer, i.e. the photodissociation region (PDR). So far there is no Zeeman detection of non-masing H RRLs; as for C RRLs, detections towards a couple of PDRs have been reported by Heiles & Robishaw (2009), and efforts are underway with LOFAR. With SKA1-MID we will be able to detect magnetic fields stronger than $100\,\mu$G in compact/ultra-compact HII regions, up to distances of a few kpc, in a few hours (by stacking hundreds of RRLs). At low frequencies, the higher angular resolution and sensitivity of the full SKA are needed to attain reasonable integration times, especially for C RRL observations.

Jets, outflows, and young stellar objects: Young stellar objects (YSOs), i.e. stars before reaching the main sequence, have an important impact in the ISM. In particular, they form HII regions, produce shocks, jets and outflows, and are a possible source of cosmic-ray acceleration. The high angular resolution of the SKA is needed first to separate different sources and corresponding flows, especially in the case of massive YSOs that are usually found in clusters, and second to resolve the different layers of shocks. Shocks are produced by the jets and outflows and will be traced with the SKA using masers (e.g. OH, H_2O, CH_3OH, NH_3), which are also tracers of high density gas. A detailed study of shock propagation will be then made by comparing observations with models (Gusdorf et al. 2015; Yvart et al. 2016; Tram et al. 2018), first fitted to sub-millimetre/infrared data. Such studies can be extended to probe the role of outflows in extracting momentum from accreting systems. The SKA will also increase the number of detected YSOs emitting synchrotron radiation and will measure their magnetics fields. Such observations will allow us to study cosmic-ray acceleration, likely occurring in these sources, magnetic field amplification, and to constrain models of relativistic electrons.

Supernova remnants: Supernova explosions are thought to be the primary source of stellar feedback in the ISM, in the form of shocks, energetic radiation, and cosmic rays. They are indeed ideal laboratories to investigate interstellar shocks. Detailed studies of shocks will be enabled by the SKA owing to its high-angular resolution, which will allow the separation and identification of the different shock components propagating into the ISM (similar to YSOs, see previous paragraph). X-ray and gamma-ray observations indicate that SNRs can accelerate particles up to TeV energies (e.g. H.E.S.S. Collaboration et al. 2011). In the thin filaments where particles are thought to be accelerated (Hwang et al. 2002), magnetic fields are more than two orders of magnitude stronger than in the diffuse ISM. However, their exact role in this process is still poorly understood. By measuring the magnetic field in these sources at high angular resolution, the SKA will shed new light on this question. In particular, it will allow us to test the existence of radio filaments. Moreover, SKA observations will be a crucial complement to SNR observations at different wavelengths (e.g. from CTA, XMM-Newton, Athena), for instance for source identification and to constrain their non-thermal spectrum.

Pulsar census and probe of the interstellar medium: The SKA will be equipped with advanced pulsar search backends, which, combined with the wide field-of-view, high sensitivity and multi-beam capabilities, will make it a true pulsar census machine. Simulations predict that SKA1 will detect about 9000 normal (young) pulsars, mostly located in the Galactic plane, and about 1500 millisecond pulsars (older), more spread across the sky. SKA2 should then detect all pulsars in the Galaxy whose radio beam is pointing our way (Keane et al. 2015). Besides enabling tests of gravity theories (particularly highly relativistic binaries), studies of old populations (e.g. their structure, magnetic field, formation history), and providing new insights into stellar evolution and accretion physics, pulsars will be ideal probes of the ISM. Notably, with pulsar dispersion measures and rotation measures we will improve models of ionised gas (thermal electron) distribution, and of Galactic magnetic fields. Moreover, the time and frequency scales of variation in the observed scintillation of pulsar radiation are a direct measure of the characteristic scale of ISM turbulence and of plasma cells. The French community, which has long term experience in pulsar timing and pulsar search, is involved in different pathfinder projects, especially using the French NenuFAR, associated with LOFAR, and the Nançay radio telescope.

Distance determination: The SKA will provide precise (microarcsecond) astrometry to astronomical objects, such as maser stars and pulsars, in the Milky Way and galaxies in the local group. This is particularly interesting to study complex regions of the Galaxy as the Galactic Bulge and the central molecular zone. The latter is a giant molecular cloud located in the inner 200 pc of the Galaxy. Precise distance and proper motions of objects in this region will allow us to understand its origin, how it interacts with the central massive black hole SgrA*, and thus to constrain the galactic potential. The SKA combined with very long baseline interferometers

(VLBI) will provide parallaxes and proper motions to better than 10 microarcseconds. Such measurements, especially in regions of high interstellar extinction, will be a valuable counterpart to Gaia observations (Ros et al. 2015). With such a precision and high cadence observations, we will also be able to measure the proper motion of SgrA*, which would provide a direct measure of the Sun-Galactic centre distance with unprecedented (1 %) accuracy. Furthermore, with precise distances to stellar clusters, we will be able to calibrate stellar mass-luminosity relations (e.g. Close et al. 2005), which are used to derive masses and ages of stars.

3 Conclusions

This article presents a brief description of the SKA project and of the engagement by the French community. It then focuses on what the SKA will bring in terms of studies of the Galactic ISM by summarising the different contributions in the Galactic Astronomy chapter of the French SKA White Book. This chapter, along with the whole Book, illustrate the large expertise of the French research community and therefore the key role that it has to play in this exciting and challenging project.

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