Chemical Complexity in the Universe: Pre-biotic Chemistry with the SKA

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Abstract

The advent of the SKA will open up the possibility to detect amino acids and other pre-biotic species in the ISM and to constrain their formation processes. It will have the potential to link their chemistry with their subsequent delivery onto protoplanetary systems and thus, with the origin of life on Earth. Furthermore, SKA will open up the possibility to study the evolution of the chemical complexity in the Universe over cosmic time.

1 Introduction

In the late 1930s, the first molecular species were found in Space with the discovery at optical wavelengths of the diatomic radicals CH and CN and the molecular ion CH^+. Thanks to the advent of radioastronomy, in the 1960s other molecules such as OH [31] and H_2O and NH_3 [8, 9] were discovered at centimeter wavelengths. Forty-five years later, more than 180 molecular species have been found in Space, which reveals an extremely high level of chemical complexity in both the interstellar medium (ISM) and the circumstellar envelopes around AGB stars (see the Cologne Database for Molecular Spectroscopy, or CDMS, for an updated list of the detected molecular species)[1].

Current studies of the chemistry in the ISM show the presence of large and heavy molecular species, some of them with more than 12 atoms in their molecular structure. These molecules are typically called Complex Organic Molecules (or COMs), and they are defined as carbon-based molecular species with more than 6 atoms in their structure [14]. It is now accepted that COMs mostly form on the surface of dust grains by atomic hydrogen addition and radical-radical reactions [13]. Most of the detections of COMs in the ISM have been

[1]See https://www.astro.uni-koeln.de/cdms/molecules.

reported toward either the central region of our Galaxy, the Galactic Center [15, 22, 26, 25]; hot molecular cores, representative of the early stages of massive star formation [6, 3, 4, 5]; or toward hot corinos, the low-mass counterparts of massive hot cores [18]. This is due to the active chemistry that these objects present as a result of the evaporation of the ices from dust grains.

This chemical complexity is not unique of regions within our own Galaxy. In the past decade, a series of works focusing on the chemical inventory toward galaxies in the vicinity of the Milky Way, have reported the detection of over 56 molecular species in nearby extragalactic sources such as the starburst galaxies NGC253 and M82, the Ultraluminous Infrared Galaxy Arp220 and the Active Galactic Nucleus NGC1068 ([20], [27], [21], [1]). In fact, it has been shown that this chemical complexity is not exclusive of our nearby Universe but it is likely present at higher red-shifts, as recently found toward the quasar PKS 1830-211 at z=0.89 [23].

In this chapter, we will present a summary of the major challenges that we will be facing in the future decades in the area of Astrochemistry and Astrobiology in both Galactic and extragalactic sources, and how the SKA will be a key instrument in our understanding of not only the chemical complexity at all scales in the Universe, but also of the chemical pathways to life.

2 Detecting amino acids in the ISM. Molecular spectroscopy at cm wavelengths

Pre-biotic species such as amino acids have attracted significant attention in the past decades due to their important role in biological processes such as the synthesis of proteins. Over 70 amino acids have been found in meteorites, which supports the idea of their extraterrestrial origin [12]. However, although several attempts have been made to detect the simplest amino acid, glycine (NH_2CH_2COOH), in the ISM toward massive hot cores [19], its firm detection is to be reported [28, 11, 17].

The discovery of amino acids in hot sources (with temperatures of a few 100 K) is indeed challenging for several reasons. Hot cores, hot corinos and the Galactic Center present very rich spectra in molecular lines whose linewidths are broad (from some to tens of km s^{-1}). In addition, previous searches mostly targeted transitions in the millimeter/sub-millimeter wavelength range where the COM spectra peak, and which gets very crowded due to the high temperatures. All this yields high levels of line blending and line confusion, which complicates the identification of molecular lines, especially of those from low-abundance species such as amino acids.

3 The potential of the SKA

One way to circumvent this problem is by observing rotational lines of amino acids at lower frequencies – and in particular at centimeter wavelengths, where the frequency span between

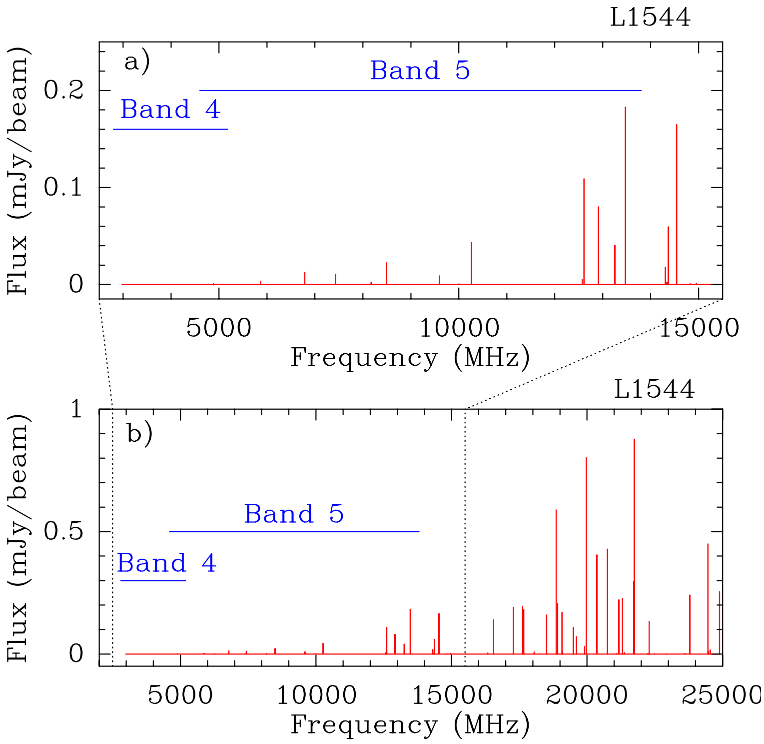

Figure 1: *Top panel:* Spectrum of glycine predicted toward the cold, pre-stellar core L1544 for the frequency range between 2.5 GHz and 15 GHz. The physical structure and gas-phase distribution of glycine is taken from [16]. The horizontal blue lines show the coverage of the SKA-MID Band 4 and Band 5 receivers. *Bottom panel:* Predicted spectrum of glycine toward L1544 for frequencies between 2.5 GHz and 25 GHz. The extension of the upper end of the frequency band of the Band 5 receivers during SKA2 will allow the detection of glycine in just few tens of hours of observing time.

transitions gets larger − significantly reducing line blending and line confusion. However, we note that *cold sources* (with temperatures below 10 K) should be targeted instead of *hot sources* at low frequencies in order to maximize the probability of detection. This is due to the fact that the peak of the amino acid (and other COMs) spectra shifts to low frequencies at cold temperatures. The SKA, therefore, represents a unique instrument for the detection of pre-biotic species in the ISM, because it covers exactly the frequency range at which the emission peak of cold amino acids is expected to be found.

This has been illustrated recently by [16], who have provided predictions for the spectrum of glycine toward the cold, quiescent pre-stellar core L1544 (a precursor of Solar-type Systems). Under some reasonable assumptions of the abundance of solid glycine in the ices (∼0.01% with respect to water ice; see [24, 7]), these predictions show that the glycine lines in pre-stellar cores reach *detectable* levels for frequencies below 80 GHz. If we extend these results to the frequency bands of SKA, we find that glycine could be detected in just a few tens of hours of observing time with the Band 5 receivers of SKA-MID (expected to cover frequencies up to 24 GHz) in its second phase (SKA2; see Codella et al. 2014).

We note that the detection of amino acids could be attempted already with SKA-MID in its first phase of operations (SKA1) by observing cold glycine and alanine i) toward protoplanetary disks in emission; and ii) toward the hot gas in the Galatic Center (background temperature of 100 K) in absorption. For the protoplanetary disk case (i), the predicted glycine emission lines arising from the cold disk mid-plane in e.g. TW Hya are expected to be ∼0.17-1.36 mJy at 15 GHz within a 3”-beam and a linewidth of $3\,\mathrm{km\,s^{-1}}$ [29]. These lines will be detected with SKA1 with a signal-to-noise ratio larger than 3 in just ∼20 hours of observing time in Band 5. For the case of the Galactic Center clouds (ii), COMs have indeed been detected toward the ISM in the Galactic Center with excitation temperatures as low as ∼5 K (see e.g. [26]). By assuming such low temperatures, the predicted intensities of the glycine and alanine lines seen in absorption against the Galactic Center are 0.7 mJy for linewidths of 20-30 $\mathrm{km\,s^{-1}}$ and within a beam of 12”. These lines will thus be detected with signal-to-noise ratios larger than 5 in just 5 hours of integration time and for a velocity resolution of $5\,\mathrm{km\,s^{-1}}$.

The advent of the SKA will therefore open up the possibility not only to constrain the formation processes of amino acids and other pre-biotic species in the ISM, but also to link their chemistry with their subsequent delivery onto protoplanetary systems and thus, the origin of life on Earth.

4 COM chemistry in the early Universe with the SKA

COM species such as methanimine, formamide and acetaldehyde have been already detected toward nearby galaxies like Arp220 [27] and the quasar PKS 1830-211 at red-shifts of z=0.89 [23]. The detection of gas-phase water at even higher red-shifts (up to z=6; [30]) indicates that grain chemistry becomes active very early-on in the Universe, suggesting that the formation of complex organics in the ices of dust grains can also occur at these cosmological time-scales.

The detection of COMs and of the precursors of pre-biotic species at high red-shifts

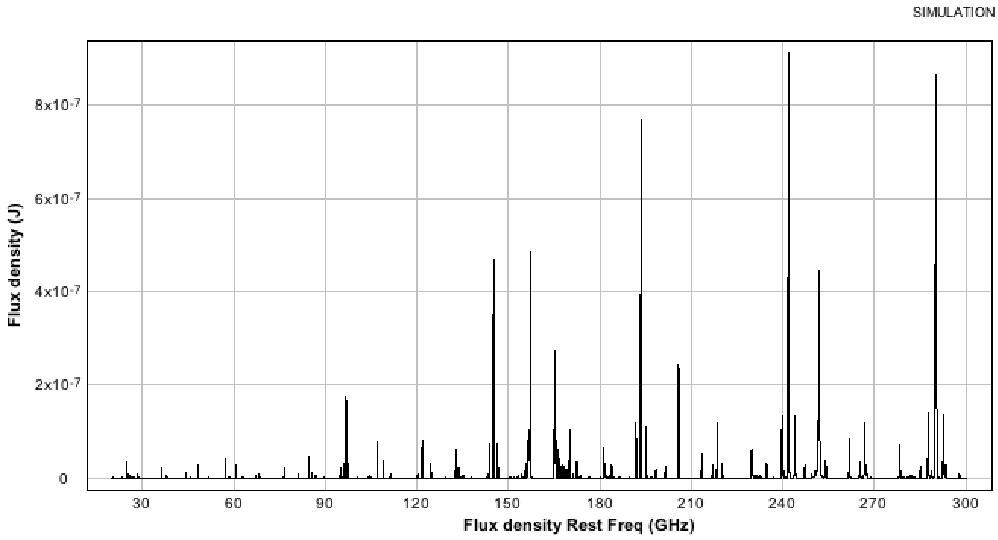

Figure 2: Simulated spectrum of the observed CH_3OH emission in the rest frame of a galaxy. The intensity scale corresponds to the observed flux density, in Jy, for a galaxy at a redshift of 7. The emission is considered to be emitted under LTE conditions with the excitation temperature corresponding to that of the Cosmic Microwave Background of T_{bg}= 2.7 (1+z) K, $\sim$ 40 K. The assumed abundance of CH_3OH is few 10^{-7}, similar to that found toward Arp220 ([21]). The CH_3OH spectrum peaks at frequencies between 150-200 GHz at the rest frame, while the observer will measure it shifted to cm wavelength, i.e. 15-25 GHz for a red-shift of z=7 (150-200 GHz/(1+z)). This frequency range is covered by the Band 5 of the SKA. For lower values of the background temperature, the peak of the CH_3OH spectrum is expected to shift to even lower frequencies covered by other SKA Bands.

however cannot be tackled in the millimeter and sub-millimeter wavelength regimes. This is due to the following. The molecular emission of COMs in galaxies peaks at millimeter/sub-millimeter wavelengths *in the rest frame*. The molecular gas will be characterized by temperatures ∼40 K since T_{bg}= 2.7(1+z) K; see Fig.2). However, as the light travels from high red-shifts to us, the peak of the COM spectra gets shifted to lower frequencies. As an example, for a galaxy at a red-shift z=7, the COM emission peak is expected to be shifted to frequencies between 15-25 GHz, which will be covered by the SKA in its phase 2 of operations.

The expected sensitivity for Band 5 at 10 GHz during SKA1 is 63 μJy $h^{-1/2}$ for a bandwidth of 100 kHz. This corresponds to 0.77 K $h^{-1/2}$ for a velocity resolution of 3 km s^{-1} in a 1"-beam. The detection, at a 3–sigma level, of the strongest and most abundant COM in galaxies, methanol (CH_3OH), assuming an abundance of few 10^{-7} (similar to that found in the 1 Kpc disk of Arp220; see [21]), would require several hundreds of hours of on-source integration time for a velocity resolution of 300 km s^{-1}. Phase 2 of the SKA will improve the sensitivity of the phase 1 by a factor of 10 which will allow to observe the methanol lines in galaxies at high red-shifts in just a few hours.

Therefore, the SKA will open up the possibility to study the evolution of the chemical complexity over cosmic time.

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