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Astrochemistry with the SRT

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Abstract. Astrochemistry is needed to study in detail the physical structure of a large variety of astrophysical environments, from diffuse interstellar clouds, to molecular clouds, to star forming regions, to protoplanetary disks, to our solar system, to external galaxies and the early universe. This paper will briefly highlight some astrochemical topics which will benefit from SRT operations.

1. Introduction: the importance of astrochemistry

Astrochemistry is a branch of astrophysics which has the aim of investigating the chemical and physical properties of the galactic and extragalactic interstellar medium (ISM), from diffuse clouds to dense molecular clouds, to star forming regions, to protoplanetary disks, to the solar system. Astrochemistry is needed to explain ISM processes and to identify the adequate tools to study in detail the space between the stars and the mechanisms which regulate star formation and galactic evolution.

Stars form in molecular clouds (e.g. Stahler & Palla 2004). Thus, the first problem that needs to be solved is how to form molecular material starting from a simple mixture of elements (Anders & Grevesse 2005; Asplund et al. 2005), in particular how to transform atomic hydrogen into H_2 molecules. The rate of formation of H_2 molecules in diffuse clouds ($n_{\rm H} \sim 100$ cm^{-3}, where $n_{\rm H}$ is the number density of hydrogen nuclei) is $R \simeq 3\times10^{-17}$ cm^{-3} s^{-1} (as derived from the Copernicus satellite; Jura 1975). Thanks to the pioneer astrochemistry work of Gould & Salpeter (1963) and Hollenbach & Salpeter (1971), we now know that H_2 is formed on the surface of dust grain particles, where two H atoms adsorb, diffuse and react, forming molecular hydrogen; upon reaction, about 50% of the formed H_2 molecules return in the gas phase (e.g. Pirronello et al. 1999; Katz et al. 1999; Cazaux & Tielens 2004; Cuppen & Herbst 2005).

Molecular hydrogen is the most abundant molecule in the Universe. Being homonuclear, H_2 is not observable in cold molecular clouds (Shull & Beckwith 1982). Therefore, one needs to find other tracers to unveil the structure and distribution of the molecular material. Carbon monoxide (CO) is the second most abundant molecule in the universe, and, in fact, it has been widely used in the past three decades to study the Milky Way (e.g. Dame et al. 2001) as well as external galaxies (e.g. Greve et al. 2005). The J=1–0 rotational transition of CO at 3 mm is however easily thermalized and it typically furnishes information on the outer layers of molecular clouds. To probe their interiors, rarer CO isotopologues (e.g. $C^{18}O$; Onishi et al. 1998) need to be observed. Moreover, in the dense cloud cores ($n_{\rm H} \gtrsim 10^5$ cm^{-3}, $T_{\rm kin} = T_{\rm dust} \lesssim 10$ K), where stellar birth takes place, CO is preferentially found in solid form on top of dust particles (e.g. Caselli et al. 1999), and other gas phase tracers have to be found. Astrochemistry has helped us in this search, and now we know that nitrogen–bearing species as well as deuterated molecules are good probes of the densest regions of molecular cloud cores (e.g. Bergin & Langer 1997; Caselli et al. 2002; Bacmann et al. 2003; Caselli et al. 2003; Tafalla et al. 2004; Crapsi et al. 2005).

Of course, astrochemistry is also invoked to understand the formation of interstellar complex species, the building blocks of life. So far, 140 molecules have been detected in space (208 including isotopes) and 50 in comets[1]. Large abundances of organic molecules have been observed in the vicinity of young high- and low-mass stars (e.g. Blake et al. 1987; Cazaux et al. 2003; Bottinelli et al. 2004), where dust grain mantles evaporate. It is likely that this material is preserved during the protostar accretion phase, transferred in the protoplanetary disks first and finally in protoplanets (e.g. Ehrenfreund & Charnley 2000). Indeed, the chemical composition of comets in our solar system is quite similar to that of the interstellar medium (e.g. Irvine et al. 2000).

A crucial molecule for life is water, which is found both in solid form in interstellar clouds with visual extinctions larger than ~4-10 mag (e.g. Whittet 1997), and in the gas phase near star forming regions (e.g. Snell et al. 2000; van Dishoeck 2004), where it plays a major role in the gas cooling (e.g. Kaufman & Neufeld 1996). It is thought that water is formed similarly to H_2 molecules, i.e. on the surface of dust grains, where oxygen atoms are adsorbed and successively hydrogenated (e.g. Allen & Robinson 1977; Tielens & Hagen 1982). Unlike H_2 molecules, water is tightly bound on dust grain surfaces and cannot evaporate in significant amounts unless the dust is either thermally heated above $\sim$ 90 K or processed in harsh environments, so that icy dust mantles are removed either via thermal evaporation (close to protostars) or via sputtering (in shocks). Mixed in water ice, other complex species can be produced (e.g. Greenberg 1984; Hasegawa et al. 1992; Caselli et al. 1993).

2. Astrochemistry with SRT

The 64-m SRT antenna will operate with high sensitivities between 0.3 and 100 GHz. This frequency range is particularly important for astrochemistry, considering that the majority of known species have observable transitions here (e.g. Johansson et al. 1985; Turner 1989; Kaifu et al. 2004).

In the next subsections I will briefly show what can be done with SRT in the field of astrochemistry. For more detailed information about the technical requirements, the reader is referred to the on-line document prepared by the SRT Working Group (Brand et al. 2005)[2].

2.1. The temperature of molecular clouds

Ammonia (NH_3) is a top-symmetric molecule, and the rotational energy is a function of the two principal quantum numbers (J,K), corresponding to the total angular momentum and its projection along the molecular axis (Ho & Townes 1983). Dipole transitions between K–ladders (states with the same value of K) are normally forbidden. This implies that the population in different K–ladders is dominated by collisions, thus it depends on the kinetic temperature. For this reason, NH_3 is a molecular cloud thermometer (e.g. Walmsley & Ungerechts 1983), and the gas temperature is typically derived from (simultaneous) observations of the (J,K)=(1,1) and (2,2) inversion transitions at 24 GHz (23.70 and 23.72 GHz, for the (1,1) and (2,2), respectively). Moreover, NH_3 is a good tracer of dense cloud cores (e.g. Benson & Myers 1989) and can then be used to locate the densest regions embedded in molecular clouds.

The SRT half-power beam width (HPBW) at 24 GHz is 50″ (7000 AU at the distance of Taurus, about one half the size of a typical dense cloud core), and, if equipped with a

[1] See http://astrochemistry.net for a constantly updated list of interstellar molecules

[2] `http://www.ca.astro.it/srt/srt_report_all_v2.ps`

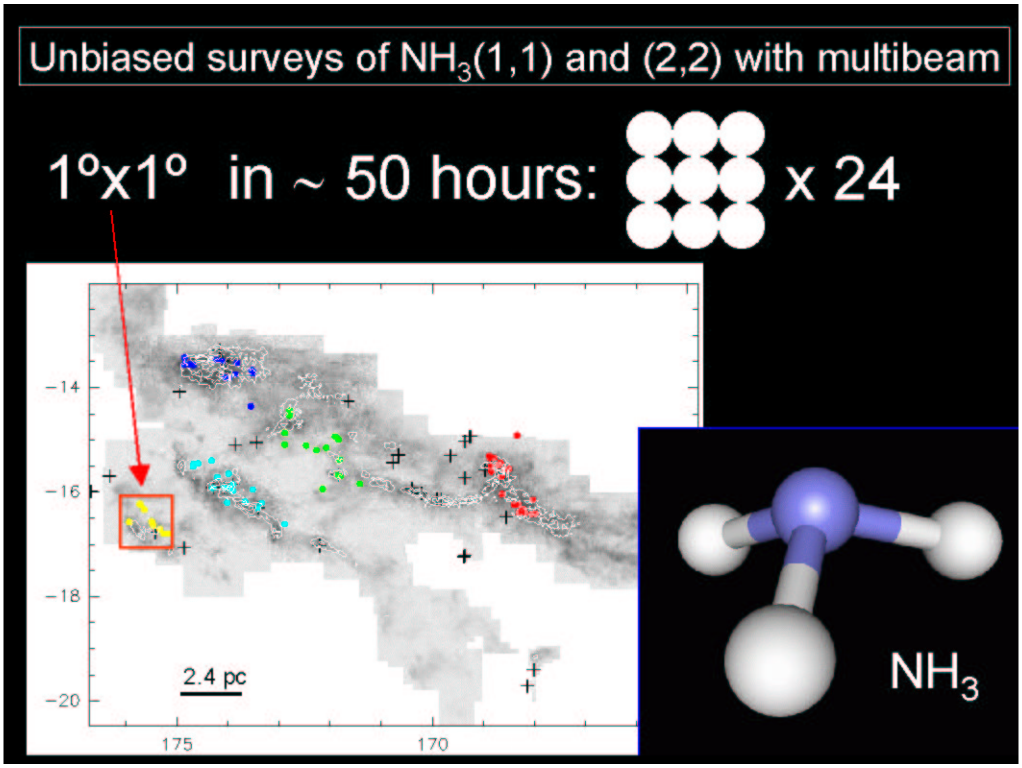

Fig. 1. The ammonia molecule (bottom-right) is a good thermometer of molecular clouds. The two inversion transitions (J,K)=(1,1) and (2,2), needed to measure the gas temperature, are close in frequency and can be observed simultaneously with SRT, with high sensitivity, and spectral and angular resolutions just ideal to study nearby star forming molecular clouds. On the left, we report the $^{13}CO(1$–$0)$ map of Taurus from Mizuno et al. (1995); the dots and crosses represent the young stellar object population (the crosses being relatively more evolved), pointing out the tight connection between molecular cloud material and star formation (courtesy of F. Palla). The square box on the left in the Taurus map is one square degree, which can be fully beam-sampled with SRT at 24 GHz in about 50 hours, if the multi-beam receiver is available. Unbiased surveys of NH_3(1,1) and (2,2) will directly measure the gas temperature, find dense cloud cores and determine the structure of the densest component of molecular clouds. This will be extremely important to put stringent constraints on current theories of star formation.

multi-beam receiver, it will be particularly suitable for unbiased studies of molecular cloud complexes and star forming regions. Figure 1 shows an example of a possible use of SRT: unbiased maps in NH_3(1,1) and (2,2), which will allow us to measure physical parameters crucial for cloud stability and evolution (such as kinetic temperature, chemical structure and internal motions) and unveil the distribution of dense cloud cores. These studies are sorely needed to understand the process of star formation, and to clarify the relative importance of magnetic fields (e.g. Mouschovias & Ciolek 1999) and turbulence (e.g. Ballesteros-Paredes et al. 2003) in the dynamical evolution of molecular clouds.

2.2. The density of molecular clouds

Rotational transitions of linear molecules can be used as (volume) density tracers of molecular clouds (e.g. Goldsmith 1999). One example is HC_3N (e.g. Bergin et al. 1996), which has at least 10 transitions observable with the

SRT. Table 1 shows these transitions, together with the associated frequency, corresponding SRT-HPBW (in angular and linear scale at the distance of Taurus), and the critical density (defined as the ratio between the Einstein coefficient of spontaneous emission and the collisional coefficient for excitation), which roughly indicates the volume density of the emitting region. Considering that dense cloud cores have typical radii of about 15000 AU and densities between 10^4 and 10^6 cm^{-3}, HC_3N observations with the SRT (Table 1) can probe the core structure from the outer layers to the densest regions.

Table 1. HC_3N rotational transitions observable with SRT. n_{cr} is the critical density of the corresponding transition.

Transition (J_u–J_l)	ν (GHz)	HPBW ($''$)	HPBW (AU)[a]	n_{cr} (cm^{-3})
1–0	9.1	130	18000	8.0×10^2
2–1	18.2	65	9000	4.0×10^3
3–2	27.3	43	6000	1.3×10^4
4–3	36.4	32	4500	3.5×10^4
5–4	45.5	26	3600	6.9×10^4
6–5	54.6	22	3000	1.2×10^5
7–6	63.7	19	2600	1.8×10^5
8–7	72.8	16	2200	2.6×10^5
9–8	81.9	14	2000	4.2×10^5
10–9	91.0	13	1800	6.0×10^5
11–10	100.1	12	1700	8.9×10^5

[a] linear size probed by the SRT for molecular cloud cores at the distance of Taurus (140 pc).

Moreover, combined HC_3N and NH_3 observations can also be used to determine the chemical age of dense cores, given that the two molecules show a different time-dependency (e.g. Herbst & Leung 1989; Ruffle et al. 1997). Other important species can be observed with the SRT antenna, in particular CCS and other carbon bearing species, useful to further constrain the cloud chemical evolution (e.g. Hirota et al. 2004).

2.3. The electron fraction

Rotational transitions of important molecular ions lie in the frequency range between 70 and 90 GHz: DCO^+(1–0) at 72 GHz, N_2D^+(1–0) at 77 GHz, HCO^+(1–0) at 89 GHz, and N_2H^+(1–0) at 93 GHz. The observation of these transitions is particularly important for the determination of the ionization degree in molecular clouds, $x(e)$ ($\equiv n(e)/n_{\rm H}$, where $n(e)$ is the number density of electrons), a crucial parameter which regulates the rate of star formation (McKee 1989). $x(e)$ cannot be directly measured in molecular clouds, but it can be gauged once the abundances of the above molecular ions are measured from observations. This is possible because the abundance of molecular ions mainly depends upon the cosmic–ray flux (responsible for the ionization of H_2 and the formation of H_3^+, which can then protonate CO and N_2 to form the above molecular ions) and the electron abundance (electrons destroy molecular ions via dissociative recombination reactions; e.g. Duley & Williams 1984). From this, it is easily found that molecular ion abundance ratios, especially those between the deuterated and hydrogenated forms of the same species (DCO^+/HCO^+ and N_2D^+/N_2H^+) are simple functions of $x(e)$ and can thus be used to trace the electron fraction (e.g. Guélin et al. 1982; Caselli et al. 1998; Williams et al. 1998).

The SRT, equipped with 3-mm receivers and the multi-beam receiver, can be used to accurately map the $x(e)$ distribution in molecular clouds. In particular, the frequency range between 70 and 80 GHz (where the ground state transitions of the deuterated molecular ions lie) is not typically (or easily) covered by available millimeter antennas (with the exception of the relatively small 12-m NRAO antenna). Thus, with high-sensitivity multi-beam receivers, the SRT can be very competitive at these frequencies.

2.4. Organic matter in space

The search for new complex molecules and the abundance of organic species in different astrophysical environments is a challenge for astrochemistry and awaits sensitive antennas and high spectral resolution receivers able to span the whole range of frequencies between 1 GHz and the millimeter range, within which many transitions of complex species with biochemical significance are present. This implies that the SRT will be particularly suitable for this search and can be used to look for complex molecules in cold clouds, and to search for new species, whose spectra have been recently measured in the laboratory (e.g. McCarthy et al. 2004). Our continuous collaborations with laboratory groups both in Italy (in particular, Bologna University) and abroad (in particular, the Ohio State University) will give us the unique opportunity to have updated lists of frequencies to be searched with the SRT. Similar work is currently being done at the Green Bank Radiotelescope (e.g. Hollis et al. 2004), but the SRT will be competitive if high sensitivity (~10 mK), large bandwidths (~1 GHz) and high spectral resolutions (~10 kHz) will be achieved.

2.5. Chemistry in compact sources

An important characteristic of the SRT is its large collecting area, crucial for studying the chemical composition of compact sources, such as protoplanetary disks and external galaxies. Compared to the only large antenna today operating at 3 mm (the IRAM 30-m antenna), the SRT will be four times more sensitive and thus will enable the search of fainter lines and less abundant gas compounds. This is important for a deeper insight in chemical processes, especially for protoplanetary disks (see the recent review by Markwick & Charnley 2004) and for the identification of spectral lines to be subsequently observed in similar objects with interferometers, in particular with the Atacama Large Millimeter Array (ALMA). The SRT can also give an important contribution to the search of crucial molecular gas coolants (such as CO and H_2O) in high-redshift galaxies ($z > 4$), currently underway (at millimeter wavelengths) at the 30-m IRAM antenna (Maiolino et al. 2005).

3. Conclusions

The Sardinia Radio Telescope has great potentialities to improve our understanding of the chemical and physical processes in the interstellar medium. Simultaneous unbiased surveys of NH_3(1,1) and (2,2) can be carried out to measure the temperature of molecular clouds, the distribution and kinematics of the dense material (where stars form) within the larger-scale molecular cloud. The volume density across the dense cloud cores can also be determined with the SRT and the chemical age can be deduced from the observation of selected molecular species. Observations at high frequencies (from 70 to 100 GHz) will allow us to measure the electron fraction. All this can definitely help to put constraints on current theories of cloud evolution and star formation. Moreover, the possibility of making unbiased spectral surveys at high sensitivity and high spectral resolution will be important for the search of complex organic molecules in space. Finally, the SRT can give an important contribution to the study of the chemical composition of protoplanetary disks and distant galaxies, thanks to its large collecting area.

To be competitive and give important contributions to astrochemistry, the SRT needs: (*i*) high sensitivity (~10 mK), (*ii*) high spectral resolution (~10 kHz), to allow the detection of the narrow features observed in cold clouds (around 0.2 km s^{-1}) and detailed studies of line profiles, (*iii*) multi-beam receivers at 20 GHz *and* 3 mm (from 70 to 100 GHz), for fast mapping; (*iv*) the frequency-switching technique (particularly useful for the narrow features observed in cold clouds); (*v*) the wobbler-switching technique, required for high mass star forming regions; (*vi*) large bandwidths (~ 1 GHz), for unbiased spectral surveys and for spectral line studies in high-redshift galaxies.

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