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The French-Spanish Large Program ASAI: Chemistry along Protostellar Evolution

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Abstract

The ASAI project addresses the important question of our chemical origins. Based on observations with the IRAM 30-m radiotelescope in Pico Veleta (Spain), it joins the efforts of nearly all specialists in Astrochemistry in Spain and France. ASAI will lead to a complete census of the gas chemical composition, including pre-biotic molecules, and its evolution along the main stages of the star formation process, from prestellar cores and protostars to protoplanetary disks. The resulting data set will remain as a reference database for astrochemists (astronomers, chemists, and theoreticians), while triggering many followup studies. It constitutes a big step forward in the understanding of molecular complexity of the infancy of our own solar system.

1 Introduction

Thanks to Herschel and the IRAM telescopes, the recent spectacular progress of radioastronomical observations now allow us to address the question of our "chemical origins" and the evolution of matter during the long process that brought it from prestellar cores, to protostars, protoplanetary disks, and ultimately to the bodies of the Solar System. Understanding this path is one of the key questions in modern Astrophysics.

Evidence is mounting that Solar System bodies have at least partially inherited material from the first phases of the Solar System formation. For example, the chemical abundances in comet Hale-Bopp were found to be similar to those in the protostellar outflow L1157 [3], and the HDO/H_2O ratio measured in the ice of comets is, within a factor of two, equal to the ocean value [11]. Moreover, the large deuteration of amino acids in meteorites suggests at least a fraction of them was formed during the first phases of the Solar System [12]. It then appears that the molecular complexity of Solar System bodies is most likely intimately related to the earliest stages of star formation.

It seems rather well established that the protostellar phase plays a major role in building up the molecular complexity, as evidenced by the recent detection pre-biotic molecules, like e.g. glycolaldehyde [7] and formamide [8] around the solar-type protostar IRAS 16293-2422. Even the prestellar cores display a rich and complex chemistry. Observations of the molecular composition of pre-stellar cores, the simplest sites where solar-type stars form, have revealed a very systematic pattern of chemical differentiation [1]. Molecular species ignored from chemical networks, like propylene, are discovered as equally abundant as other well-known hydrocarbons.

Despite a wealth of fragmentary studies in the literature, the current picture of the chemical evolution of protostellar systems is still very incomplete and key questions remain unanswered. What explains the chemical differentiation observed in protostellar objects? When, where, how does deuteration sets in? How do complex organic molecules, hydrocarbons, ions form? What are the formation routes, the evolutionary timescales, the role of non-thermal processes?

In order to address these questions, we have undertaken an international collaboration, gathering nearly all the specialists in astrochemistry in France and in Spain to conduct with the IRAM 30m telescope in the Sierra Nevada (Spain) a systematic spectral line survey of a sample of 10 objects representing the various phases the Sun and our Solar System passed through, from prestellar cores to protoplanetary disks. ASAI can be seen as the culmination of a long standing collaboration among the Spanish and French teams, as both PIs and team members have very deep imbrications with each others country, as associated researchers for a long time. The ASAI team comprises about 35 scientists from 10 laboratories, mainly in France and Spain, with a few other partners located in Europe, Japan, and Brazil.

2 ASAI

2.1 Spectral Line Surveys

Systematic spectral line surveys constitute the most powerful diagnostic tool to carry out a comprehensive study of the chemical evolution of star-forming regions. In general terms, as different lines from transitions with different upper level energies and Einstein coefficients are excited at different temperatures and densities, line surveys permit to probe different regions along the line of sight. Star-forming regions are particularly complex because of the chemical differentiation of different regions (different chemical species are predominant in different cloud zones) and because different lines from the same species are excited under different conditions (temperature, density, velocity field, etc), with sometimes complex kinematics, where infall and outflow motions are simultaneously present.

Despite numerous fragmentary observations at all stages of protostellar evolution, unbiased spectral surveys of low-mass, solar-type object have been carried out only towards IRAS16293 [2, 5] and towards L1527 at 3mm only [14].

The new capabilities of the IRAM 30-m telescope have made possible to take a major step forward in the investigation of molecular complexity along with star formation, by

Table 1: Source sample, properties (distance, luminosity). Sources observed in CHESS, WISH, and Open Time are indicated by C, W, OT1, respectively.

Type	Source	d (pc)	L ($L_\odot$)	Herschel	Comment
PSC	L1544	140	-	C, W	Evolved: high deuteration
	TMC1	140	-	OT1	Young : hydrocarbon rich
Class 0	B1	200	-	-	Early : no outflow, high deuteration
	IRAS4A	250	7.7	C,OT1	Hot Corino
	L1527	140	2	W	WCCC
	L1157mm	250	4	W	WCCC ? comparison with B1
Class I	SVS13A	250	43	W	Evolved
Class I-II	AB Aur	145	-	OT1	residual envelope, warm disk
Jet	L1448	250	(11.6)	W,OT1	EHV bullets
Bowshock	L1157-B1	250	(4)	C,W	MHD shock prototype

observing with unprecedented sensitivity the emission of molecular rotational transitions in the millimeter domain in a greatly reduced amount of time. Taking advantage of the new generation of EMIR receivers and the broad-band FTS spectrometers, which provide 32 GHz of instantaneous bandwith at 200 kHz resolution, the goal of ASAI is to obtain an unbiased spectral exploration of a carefully selected sample of template sources at an rms better than $\approx 5mK$ in the three millimeter windows (80-116GHz; 130-170 GHz; 200-272 GHz). Such a sensitivity provides us with a full census of the chemical species present in the gas phase down to abundances as low as 10^{-12} with respect to H_2.

The measured abundances will then be compared to state of the art astrochemical models, providing a laboratory where the various parameters which any model depends on, are covered by the selected sources. Source inter-comparison will permit to better constrain the parameter space, in particular assess the importance of age and/or the physical conditions. In addition to the discovery of new molecular species, and the revision of the astrochemical models, we certainly expect new detections and surprises, which will trigger small, follow up observations with both IRAM instruments.

2.2 Source sample and Observations

We have selected a sample of template sources providing a complete view of the different types of objects encountered along protostellar evolution (Table 1) : 2 prestellar cores (one chemically evolved, one young), Class 0 sources with/without fully developed outflows, including solar-type hot corino and WCCC candidates, a more evolved, Class I protostar, and a young star in the Class I/II transition, with an apparent protoplanetary disk and a residual protostellar envelope, two outflow shock regions with/without extremely high-velocity molecular bullets. These objects have all been/are the subject of molecular gas studies at millimeter wavelengths in our team, and maps of the molecular emission and the velocity field are available for several molecular species.

2.3 The IRAM-Herschel synergy

For most of the sample sources, the emission of the major gas cooling agents in the hot/warm gas phase has been observed with HIFI in the course of the Herschel Key-Projects WISH [15] and CHESS [6] and several open-time proposals (see Table 1). The complementarity of the IRAM and Herschel data offers an unprecedented view on the protostellar environments and their chemical evolution. Herschel gives access to the hot protostellar gas regions, probed by heavy molecules, and to some cold gas regions, as probed by the low-energy transitions of light hydrides (see e.g. [6]). The IRAM contribution is essential: on the one hand, the mm-wave spectral range fully probes the physical and chemical conditions of the cold gas component; on the other hand, the high-sensitivity of the EMIR receivers permits now to obtain a full census of the chemical species, hence the molecular complexity present in the gas phase: neutrals (including complex organic species released/synthesized in the gas phase), anions and cations, which are involved in the chemistry, thermal state, and dynamics of the gas.

3 First Scientific Results and Prospects

At the time of the SEA conference, the data acquisition has just been completed and the project is now entering an active exploitation phase, with 18 months of proprietary time ahead. Reduction and consistent calibration of such a large amount of data is a real challenge, even for the experts in radioastronomy of the team! An example of the power of ASAI is illustrated in Fig. 1, which shows the spectral signature of the whole source sample between 85 and 88 GHz. Spectacular changes in the detected spectral lines are observed from source to source tracing the chemical evolution from a pre-stellar core to a protostar and a protoplanetary disk. New molecular species have been discovered, both in prestellar cores [4] and in protostellar shocks [10], opening the door to pre-biotic chemistry in these environments [9]. The excellent sensitivity of the ASAI spectra permitted the discovery of the long-searched jet powered by the template Class 0 protostar L1157-mm [13].

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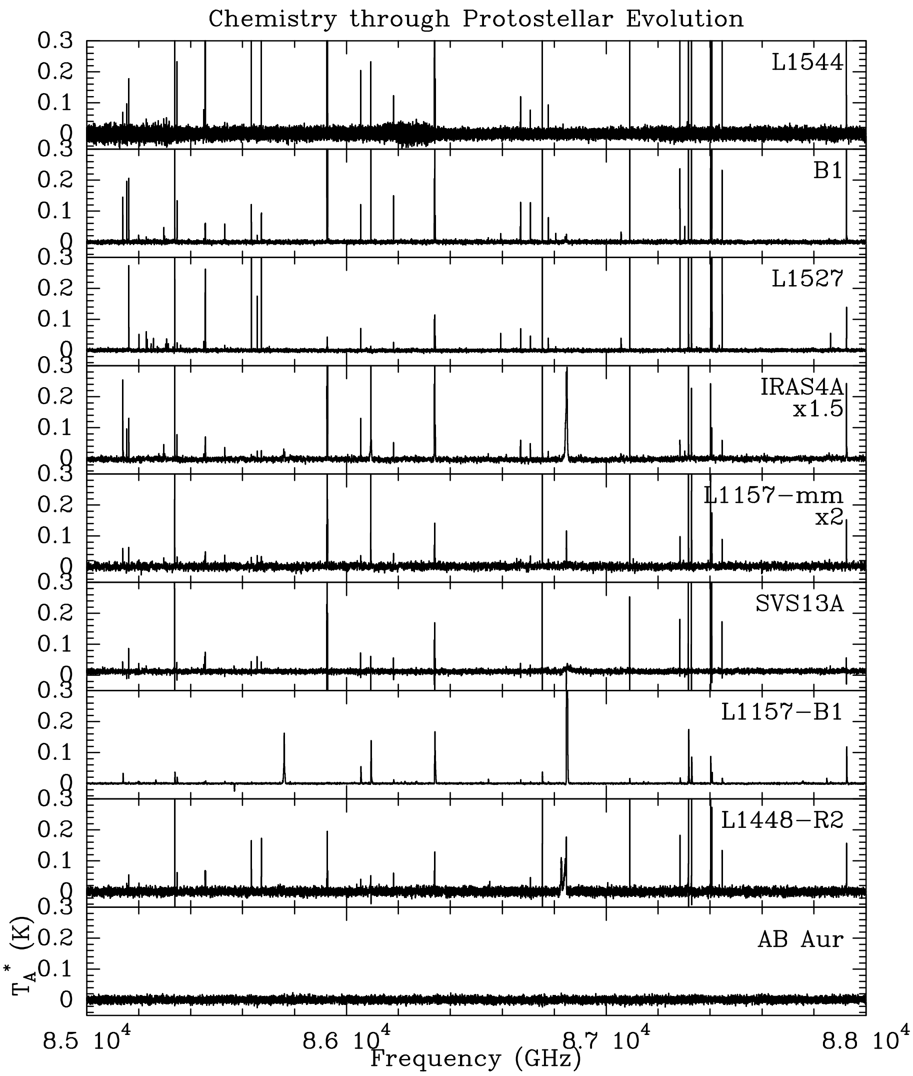

Figure 1: Spectra in the range between 85 and 88 GHz for the 10 ASAI targets. Note the important differences from source to source trace the chemical evolution from a pre-stellar core (L1544) to a protostar (such as L1157-mm) and a protoplanetary disk (AB Aur).

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