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Multi-line Diagnostics of the Interstellar Medium

Shocks in the surroundings of the NGC 1333 IRAS 4 system

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Abstract. The IRAS 4A system is part of the southern filament of the Perseus NGC 1333 molecular cloud. As most of the star forming regions, NGC 1333 is known to be heavily shaped by external triggers, such as shock fronts around OB stars or supernovae remnants, cloud-cloud collisions, and instabilities. Recently, it has been hypothesized that the entire southwest region of NGC 1333, encompassing the filament where IRAS 4A lie, is due to a colliding "turbulent" cell, a clash that triggered the birth of the protostars on the filaments. However, no specific signatures of a clash have been reported so far, leaving unanswered how and where the energy of this clash, if real, is dispersed. To answer this question, we analyzed new high spatial resolution (~600 au) observations of CH_3OH and SiO, known shock tracers, obtained in the context of the Large Program IRAM/NOEMA SOLIS searching for specific signature of the clash event. We detected three parallel elongated structures, called fingers, with narrow line profiles (~1.5 km s^{-1}), peaked at the systemic velocity of the cloud, tracing gas with high density (5-20×10^5 cm^{-3}) and high temperature (80-160 K). They are chemically different with the northern finger traced by both SiO and CH_3OH and the other two only by SiO. Among various possibilities, a train of three consecutive shocks, due to an expanding bubble coming behind NGC 1333 and from the southwest, can reproduce the observations. Finally, we propose a solution for the two-decades long debate on the nature and the origin of the widespread narrow SiO emission observed in the south part of NGC 1333, namely unresolved trains of shocks.

1 Introduction

The Perseus molecular cloud is a nearby [orders of 300-400 pc; 1]) giant molecular cloud characterized by a large population of low-mass young stellar objects, of which the majority is associated with the two major clusters IC 348 and NGC 1333. In particular, the latter is one of the most active sites of on-going star formation [e.g., 2].

Like most of the star forming regions, NGC 1333 is characterized by filaments and cavities that, together with a clear velocity gradient (see Figure 1), suggest that it has been shaped by external triggers (such as, ionization/shock fronts by stellar winds or supernovae remnants, cloud–cloud collisions, and instabilities). In particular, Dhabal et al. [3] hypothesized that the entire blue-shifted southwest region of NGC 1333 is due to a colliding "turbulent cell", a clash that created the filament and triggered the birth of the protostars on it. However, no specific signatures of a clash, namely shocks, have been reported so far, leaving unanswered how and where the energy of this clash, if real, is dispersed.

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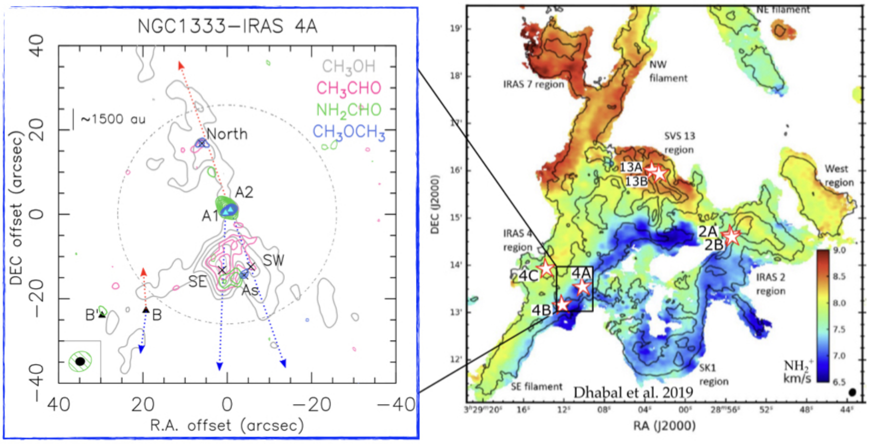

Figure 1. *Right*: N_2H^+ (1-0) velocity map of NGC 1333 south [3]. The main protostellar cores are marked with white stars. *Left*: iCOMs contour emission in the IRAS 4A outflows observed with NOEMA/SOLIS Observations [4]. The dashed blue and red arrows indicate the direction of outflows.

2 NGC 1333 IRAS 4: A region full of surprises

One of the protostellar systems that lies along the NGC 1333 southern filaments is IRAS 4 [distant ~300 pc; 1]. It is characterized by the Class 0 protostar IRAS 4B and the protostellar binary system 4A composed of 4A1, the brightest in mm continuum, and 4A2 separated of 1.″8, driving a spectacular large bipolar outflow [e.g., 5–8].

2.1 The molecular complexity of IRAS 4A outflows

As part of the NOEMA SOLIS[1] Large Program, we analyzed the molecular emission of the IRAS 4A outflows. The high angular resolution and high sensitivity observations allowed us to detect and image, for the first time, several interstellar Complex Organic Molecules (iCOMs) in the IRAS 4A outflow (see Figure 1): the methanol emission is extended (~ 1′) and covers the lobes of the two outflows, the acetaldehyde emission traces intermediate scales (~ 15″) and it is bright toward the southern-east lobe, the dimethyl ether and formamide emissions are compact and not resolved in two position along the outflows [4].

Analyzing the emission in different positions of the outflows, and focusing on methanol and acetaldehyde, we confirmed the presence of chemical differentiation, with the southeast lobe (driven by 4A1) brighter in iCOMs than the southwest-north (driven by 4A2). As explained in full details in De Simone et al. [4], comparing the observations with astrochemical model predictions we could test the formation path of the acetaldehyde suggesting that it is synthesized in the gas phase by the reaction of atomic oxygen with ethyl radical.

2.2 Elongated structures around IRAS 4A

While analyzing the methanol emission in the IRAS 4A outflows, we noticed the presence of an elongated structure almost perpendicular to the outflow with a narrow spectral profile (FWHM~1.5 km s $^{-1}$) peaking at the systemic velocity of the cloud. Similar structures were

[1] Seed Of Life in Space; https://solis.osug.fr

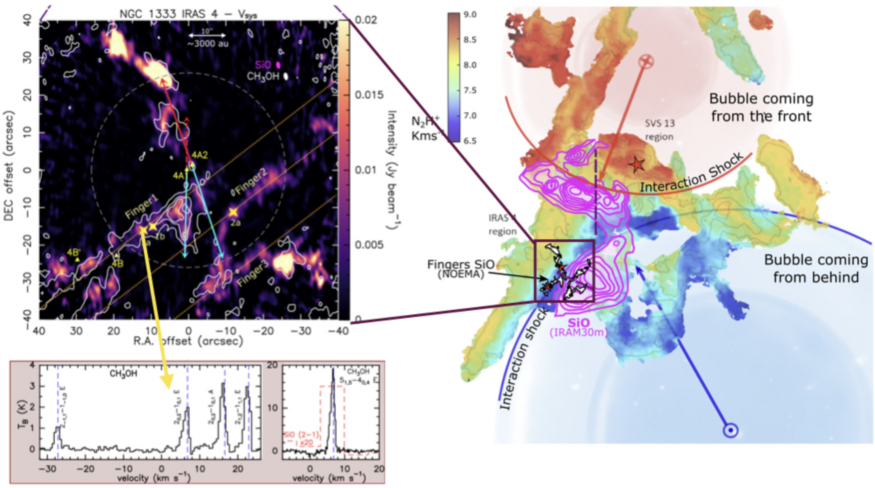

Figure 2. *Upper left*: emission of the three fingers, marked by orange lines, in SiO (color scale) and CH_3OH (contours) observed with NOEMA SOLIS [12]. *Bottom left* CH_3OH (black) and SiO (red, magnified by a factor of 20) spectra extracted at the Finger1a position. *Right:* Large-scale view of NGC 1333 south overlapping the N_2H^+ velocity map by Dhabal et al. [3] with our SOLIS SiO fingers, and the IRAM 30m widespread narrow SiO emission by Lefloch et al. [9]. The red and blue curves represent the interaction of the expanding bubbles: The former is expanding from the north-west towards SVS13 from the front, and the latter is expanding from the south-west towards IRAS 4A from behind.

observed in SiO by Choi [5] with the VLA in the southwest part of the region, and by Lefloch et al. [9] and Codella et al. [10] with IRAM 30m observations as a widespread SiO emission connecting the IRAS 4A region with the SVS13 one.

In order to understand if these features were related to each other we analyzed our NOEMA/SOLIS observations of CH_3OH and SiO (see Figure 2). We identified three parallel fingers separated by about 10″ (∼3000 au): i) Finger1, traced by CH_3OH and SiO, is the northern one; ii) Finger2, traced only by SiO, is 10″ south to Finger1; iii) Finger3, traced only by SiO, is an additional 10″ south. While Finger2 and Finger3, detected only in SiO (2-1), are perfectly in agreement with the SiO (1-0) VLA observations by Choi (2005), Finger1 was never detected before and it is traced by both CH_3OH and SiO. Additionally the fingers are located in the large-scale blueshifted southern region of NGC 1333 (see Figure 2).

Analyzing the methanol and SiO emission using a non-LTE LVG analysis [11] as described in details in [12], we derived the gas properties and the SiO/CH_3OH abundance ratio in Finger1 and Finger2. We confirmed the chemical diversity observed in the fingers, and we found that they are tracing material at high density ($> 10^5$ cm^{-3}) and high temperature (> 80 K). However, what is their origin?

We investigated two main possibilities: the fingers are tracing i) Kelvin Helmholtz instabilities or ii) a train of shocks. However, even if the former could reproduce the quasi periodicity of the fingers, it could not reproduce the observed gas density and temperature. Therefore, the only plausible possibility was a train of shocks, well justified by the presence of both SiO and methanol, and by the derived gas physical condition.

3 Train of shocks as a signature of an unexpected clash

Given that methanol is efficiently formed on the grain mantles through the CO hydrogenation in the prestellar phase, the gaseous methanol observed in the fingers must have been extracted from the grain mantles and injected into the gas phase. The same applies to the observed SiO. The observed chemical differentiation in the fingers can be explained in two ways: the two species are injected from the grains with i) different abundance ratio in the different fingers or ii) the same abundance ratio that changes in time because of chemical processes occurring in the gas phase.

To investigate that, we compared the observed CH_3OH/SiO abundance ratio with astrochemical model predictions putting constraints on when the shocks occurred: the northern finger is the youngest one and it happened at least 5000 yr after the next southern one. Therefore, we suggest that the three fingers are the result of a successive train of shocks created by the clash of an expanding bubble coming from south-east and moving towards the IRAS 4A main cloud from behind [12].

Finally, we suggest that the widespread narrow SiO emission observed towards the NGC 1333 IRAS 4 and SVS 13 region with single-dish observations in the late 1990s [9, 10] is due to unresolved trains of shocks like the SOLIS fingers. These shocks would be the signature of the interaction of the bubble giving rise to the IRAS 4A fingers in the south and of another bubble pushing from the north towards SVS 13.

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