Onsala Proposal

Cosentino 0108.F-9306

Interstellar Plunging Waves: The Inception of Star Formation (resubmission of accepted proposal 0107.F-9315)

Semester: may2021 **Science Cat.: ISM and star formation**

Abstract

Despite the importance of massive stars for the energy content and evolution of galaxies, the mechanism that ignites their formation in molecular clouds is still poorly addressed. Infrared Dark Clouds (IRDCs) are the likely precursors of such objects. It has been suggested that IRDC formation from the diffuse atomic medium through multiple shock episodes triggered by bubbles can efficiently initiate star formation within these clouds. It is thus important to understand the conditions of density and temperature set by large-scale shocks in IRDCs and to compare them with those required for massive stars and star cluster formation. Recently, we have investigated the SiO(2-1) emission at the shock interaction layer between the Supernova Remnants W44 and the IRDC G034.77-00.55. Here, we propose to use APEX to complement this study by observing the SiO(5-4) transition toward the shock. We will couple the new observations with data already in hand to infer the density enhancement and excitation state of the shocked gas and compare them to those required for massive star formation.

Applicants

Name	Affiliation	Email	Country		Potential observer
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Applicants are continued on the last page

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		Remarks	Country is Sweden

Is this a long term proposal: No

No overall scheduling requirements

Observing runs

run	telescope	instrument	time request (minimal)	frequency (GHz)	weather (pwv)	LST range	comments/constraints
A	APEX	nFLASH230 (200-270 GHz)	15h (15h)	219	> 2 mm	15-22	We intend to use the instrument by tuning at a frequency of 219 GHz, in lower side band. We will use double side band configuration in dual polarisation mode. Sun Avoidance 18 Dec-25 Jan

Targets

Source	RA	Dec	Epoch	Vlsr (km/s)	Duration (min)	Runs	Comments
G034	18:56:43.20	+01:23:25.6	J2000	42.0	900	A	

Scientific Rationale

Introduction. Although massive ($\geq$8 $M_\odot$) stars and star clusters play key roles in the evolution of galaxies, their formation is still poorly understood. Crucial information on the problem can be found from the study of Infrared Dark Clouds (IRDCs), cold (T$\leq$25 K) [1,2], dense (n(H_2)$\geq 10^3$ cm^{-3}) and massive (> 1000 $M_\odot$) [3] molecular structures believed to represent the initial conditions of massive stars and stellar clusters. Simulations have shown that both the IRDC formation process [4,5,6] and the dynamical interactions that they undergo during their lifetime [7,8], can efficiently initiate star formation within the cloud. Among current theories, [9] suggested that IRDCs can form as the result of multiple shock compression episodes acting on atomic and molecular gas, driven by bubbles as, e.g., supernova remnants (SNRs) or HII regions (see Figure 1). At the same time, already formed IRDCs can be processed by nearby stellar feedback events as e.g. supernova explosions or HII regions (SNRs)[10]. In both cases, the density enhancement caused by the shock propagation may be enough to trigger the formation of massive stars in the IRDC [11,12]. It is thus crucial to quantitatively investigate how shocks induced by stellar feedback affect the physical conditions of temperature and density of the molecular gas in IRDCs. Hence, **we propose to map shock tracer emission toward an IRDC interacting with molecular gas pushed away by a SNR**. The new observations, coupled with data in hand, will enable us to study the physical conditions of the shocked gas and how these relate to the initial conditions of massive star formation.

Previous Studies. The IRDC G034.77-00.55 is known to be interacting with the shock wave driven by the nearby SNR W44 [13,14]. The interaction can be interpreted as one of the multiple shock episodes in the [9] theory. Toward this IRDC, our group has performed a detailed study of the kinematic structure of the Silicon Monoxide, SiO(2-1), emission arising from the shock [12,15]. SiO is a unique shock tracer whose abundance can be enhanced up to a factor $\sim 10^6$ in shocked regions, but that remain heavily depleted in quiescent regions ($\chi \sim 10^{-12}$)[16,17]. The ALMA observations that we presented in [12], have shown that the shock wave probed by the SiO emission in G034.77-00.55 is in the act of plunging into the cloud, compressing the gas to values compatible with those required to ignite star formation (n(H_2) $\geq 10^6$ cm^{-3}). In addition, we have spatially resolved, for the first time, the internal physical structure of the shock [12], identifying its C and J-type components as predicted by [18] (Figure 2). *All this suggests that the interaction layer between G034.77-00.55 and W44 is the optimal site to investigate the initial conditions of star formation in IRDCs.*

Objectives. We propose to use APEX to map the SiO(5-4) emission toward the shock layer in G034.77-00.55. The excitation of the SiO (5-4) line emission requires high density and excitation temperature and hence will allow us to probe the kinematics of the gas transitioning from the J to the C-type shock component. Such gas is predicted to be experiencing the maximum compression. We will also use the new data together with already in hand SiO(1-0), (2-1) and (3-2) emission maps to build rotational diagrams across the shock, to disentangle between the contribution of the C and J-type shock components. In fact, since the C-type and J-type components correspond to two different excitation states, rotational diagrams are expected to show two different rotational temperatures. *The four transitions represent the minimum required information to identify the two temperatures.* Finally, using the Large Velocity Gradient (LVG) code RADEX [19] to model the several observed SiO transitions, we will estimate the H_2 gas density and kinetic temperature across the shock. Hence, we will compare the obtained values with those required for the formation of massive cold cores, the earliest known phase of massive star formation. Current models predict massive cores to be formed in regions of molecular clouds with local density $>10^5$ cm^{-3} (e.g. [20]). Such values are compatible with those probed by SiO transitions with J>2 (critical density $>10^5$ cm^{-3}) and hence can be recovered with the proposed analysis. This comparison will ultimately allow us to observationally prove that initial conditions of massive star formation can be induced by SNR feedback in molecular clouds.

Facilities Requested

We request to use the APEX 12m antenna to map the SiO J=5-4 rotational transition toward the IRDC G034, known to be undergoing a MHD shock. With its receiver nFLASH230, APEX is a unique facility to fulfil our scientific goal, since it allows to efficiently observe relatively high-transitions in reasonable integration times. The same observations would indeed require more than 300 hours of observing time with other facilities e.g., IRAM 30m telescope.

Observing Requirements

We propose to use ∼15 hours of the APEX 12m telescope observing time to perform a high-sensitivity OTF map of the SiO(5-4) transition, toward the shocked region of the IRDC G034 (Figure 2). Observations will be performed in position switching mode with field of view $100'' \times 100''$. The receiver nFLASH230 will be used with tuning frequency at 219 GHz in Lower Side Band (LSB) and observations will be performed in dual polarization mode. From previous observations toward G034, the SiO lines show linewidth <5 km s^{-1}, so we request a velocity resolution of 0.5 km s^{-1}, sufficient for the proposed analysis. By using the SiO(1-0), SiO(2-1) and SiO(3-2) emission already in hand, we have used the LVG code RADEX to infer the line intensity of the SiO(5-4) emission. Assuming kinetic temperature T_{kin}=10 K, molecular hydrogen column density (H_2)=4.5×10^4 cm^{-3} and SiO total column density 10^{13} cm^{-2}, the intensities of the known transitions are reproduced and the SiO(5-4) line intensity is predicted to be 0.035 K toward a beam aperture of 45″. This corresponds to a SiO(5-4) line intensity of 0.015 K toward the APEX beam aperture of 30″. We note that the assumed T_{kin}=10 K is a conservative value and that the shocked gas is likely to be warmer. In order to achieve a signal-to-noise ratio S/N>3, we request a sensitivity of 5 mK per beam. With these observing requirements and assuming PWV∼2 mm and elevation∼45°, the estimated requested time is 15 hours (including overheads). We note that the chosen frequency set up has the advantage to not just cover the SiO(5-4) transition, but also DCO^+(3-2),^{13}CO(2-1), ^{13}CN(2-1) and CO(2-1). For all these species we have previously obtained the corresponding ground state transition and hence they can be used to complement the main goal of the proposal by also studying the excitation conditions of the pre- and post-shocked gas. We note that this proposal is a re-submission of the project 0107.F-9315. The project 0107.F-9315 was accepted in the last APEX cycle but observations may not be carried on due to the increasing restrictions related to the COVID-19 pandemic. We are thus re-submitting the proposal and will withdraw it in case of completed observations.

References

[1] Pillai et al. 2007, A&A, 467, 207 • [2] Ragan et al. 2011, ApJ, 736, 163 • [3] Rathborne et al. 2006, ApJ, 641, 389 • [4] Hennebelle et. al 2008, A&A, 486, L43 • [5] Heitsch et al. 2009, ApJ, 695, 248 • [6] Tasker & Tan 2009, ApJ, 700, 358 • [7] Klessen & Glover 2016, Star Formation in Galaxy Evolution: Connecting Numerical Models to Reality, Saas-Fee Advanced Course, Volume 43. ISBN 978-3-662-47889-9 • [8] Kruijssen et al. 2019, Nature, 569, 519 • [9] Inutsuka et al. 2015, A&A, 580, 49 • [10] Tackenberg et al. 2013, A&A, 550, A116 • [11] Jimenez-Serra et al. 2010, MNRAS, 406, 187 • [12] Cosentino et al. 2019, ApJL, 881, L42 • [13] Wooten et al. 1977, ApJ, 216, 440 [14] Sashida et al. 2013, ApJ, 774, 10, 7 • [15] Cosentino et al. 2018, MNRAS, 474, 3760 • [16] Martín–Pintado et al. 1992, A&A, 254, 315 • [17] Jimenez-Serra et al. 2005, ApJL, 627, L121 • [18] Draine et al. 1980, ApJ, 241, 1021 • [19] van der Tak et al. 2007, A&A, 468, 627 • [20] Völschow et al. 2017, A&A, 605, A97 • [21] Carey et al. 2009, PASP, 121 • [22] Churchwell et al. 2009, PASP, 121 • [23] Beuther et al. 2016, A&A, 595 • [24] Kainulainen & Tan 2013 A&A, 54 • [25] Flower et al. 2015, A&A, 578 •

Figures

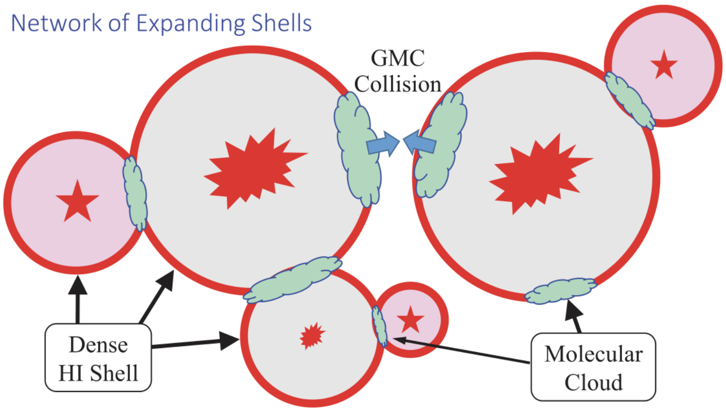

Figure 1: **A schematic picture of sequential formation of molecular clouds by multiple compression by overlapping dense shells driven by expanding bubbles.** The thick red circles correspond to magnetized dense multi-phase interstellar medium where cold turbulent HI clouds are embedded in warm neutral medium. Adapted from [9].

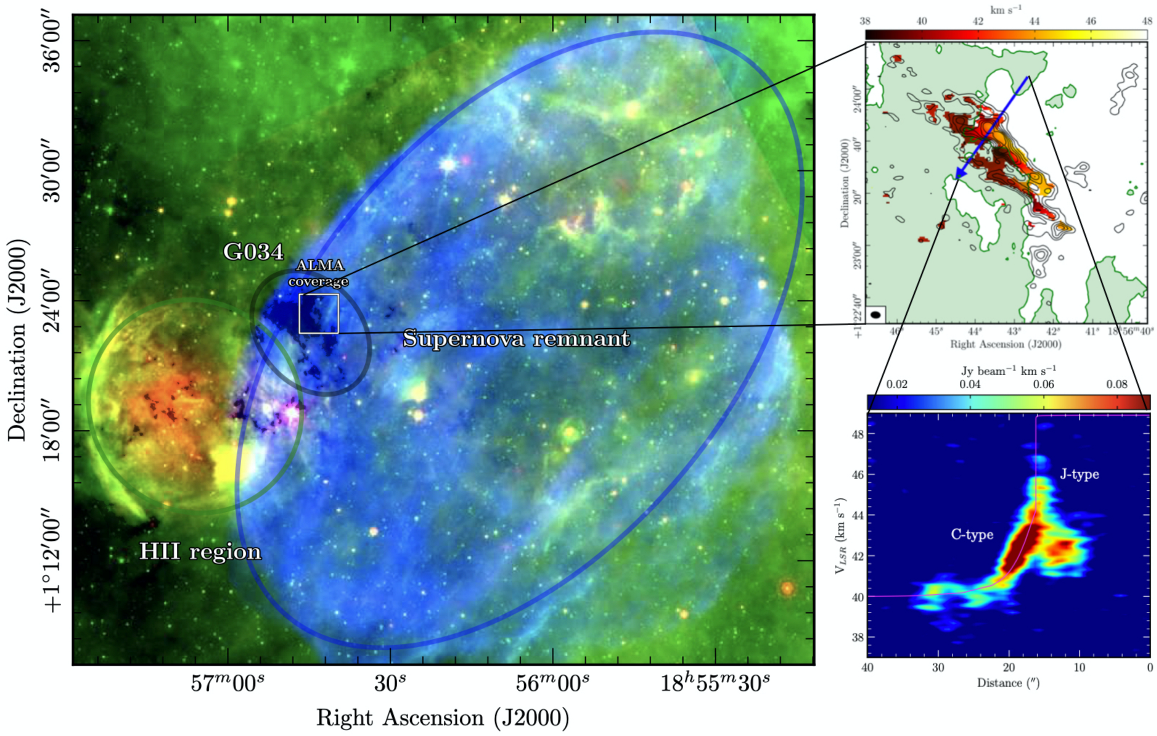

Figure 2: **Left: Relative position between G034.77-00.55 (black circle) and the SNR W44 (blue circle).** Red is 24 μm emission (Spitzer MIPSGAL)[21], green is 8 μm emission (Spitzer GLIMPSE)[22], and blue is 21 cm emission (THOR survey)[23]. Top right panel: SiO integrated emission contours (from 3σ by 3σ; σ = 0.016 Jy km s^{-1}) superimposed on its moment 1 velocity map (red scale). The green contour and shadow correspond to Av$\geq$20 mag [24]. Bottom right panel: Position-velocity diagram showing the internal structure of the shock detected in SiO toward the IRDC. Magenta line indicate the best model fit obtained obtained using the Paris-Durham MHD shock code [25].

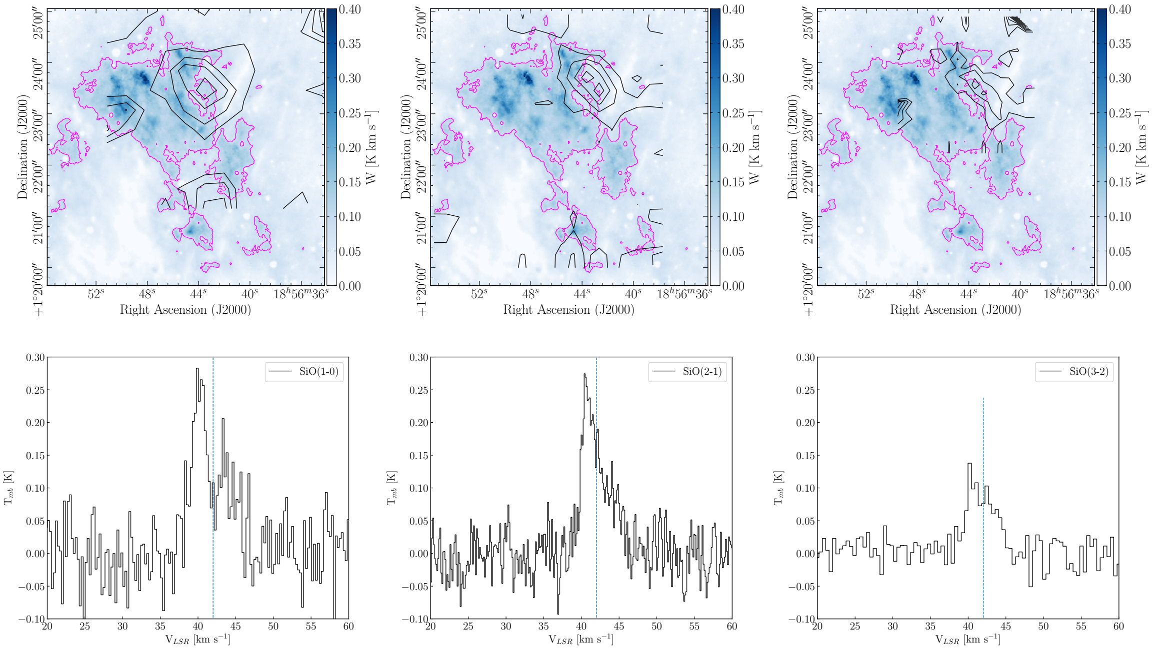

Figure 3: **Integrated intensity maps (top row) and average spectra (bottom row) of the SiO(1-0), (2-1) and (3-2) emission lines (from left to right) in G034.77-00.55.** The SiO(1-0) transition has been observed with the RT40m telescope, the SiO(2-1) [15] and SiO(3-2) using IRAM30m. For all lines, integration velocity range is 39-46 km s^{-1} and contours are from 3σ by steps of 3σ (σ = 0.1 K km s^{-1} in all maps). The magenta contour corresponds to the 20 mag visual extinction level [24].

Students involved

Student	Level	Applicant	Supervisor	Applicant	Expected completion date	Data required
Mr. Chi Yan Law	Doctor	Yes	Prof Jonathan Tan	Yes	2023/12	No
Chia-Jung Hsu	Doctor	Yes	Prof Jonathan Tan	Yes	2022/12	No

Linked proposal submitted to this TAC: No

Linked proposal submitted to other TACs: No

Relevant previous Allocations: Yes

This is a resubmission of the accepted proposal with project code 0107.F-9315.
Since it is unsure whether the project will be observed we are now resubmitting and we will withdraw the proposal if the observations will be carried on.

Additional remarks

ESO=<gcosentino>

Observing run info :

Applicants

Name	Affiliation	Email	Country		Potential observer
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