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# Negative and Positive Feedback from a Supernova Remnant with SHREC: A detailed Study of the Shocked Gas in IC443

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## ABSTRACT

Supernova remnants (SNRs) contribute to regulate the star formation efficiency and evolution of galaxies. As they expand into the interstellar medium (ISM), they transfer vast amounts of energy and momentum that displace, compress and heat the surrounding material. Despite the extensive work in galaxy evolution models, it remains to be observationally validated to what extent the molecular ISM is affected by the interaction with SNRs. We use the first results of the ESO-ARO Public Spectroscopic Survey SHREC, to investigate the shock interaction between the SNR IC443 and the nearby molecular clump G. We use high sensitivity SiO(2-1) and H<sup>13</sup>CO<sup>+</sup>(1-0) maps obtained by SHREC together with SiO(1-0) observations obtained with the 40m telescope at the Yebes Observatory. We find that the bulk of the SiO emission is arising from the ongoing shock interaction between IC443 and clump G. The shocked gas shows a well ordered kinematic structure, with velocities blue-shifted with respect to the central velocity of the SNR, similar to what observed toward other SNR-cloud interaction sites. The shock compression enhances the molecular gas density,  $n(\text{H}_2)$ , up to  $>10^5 \text{ cm}^{-3}$ , a factor of  $>10$  higher than the ambient gas density and similar to values required to ignite star formation. Finally, we estimate that up to 50% of the momentum injected by IC443 is transferred to the interacting molecular material. Therefore the molecular ISM may represent an important momentum carrier in sites of SNR-cloud interactions.

**Key words:** ISM: clouds; ISM: supernova remnants; ISM: kinematics and dynamics; ISM: individual objects: IC443, clump G.

## 1 INTRODUCTION

Massive stars ( $M \geq 8 M_\odot$ ) drive powerful stellar feedback that profoundly affects the evolution and star formation efficiency (SFE) of the hosting galaxies. Of such mechanisms, feedback driven by Supernova explosions (SNe) is among the most energetic (Bally 2011) and long-lasting (e.g., Leitherer et al. 1999; Agertz

et al. 2013). As the remnant expands, the hot plasma pushes and compresses outwards the atomic and molecular gas in contact with the remnant (Chevalier 1974) and injects energy, mass and momentum into the interstellar medium (ISM), profoundly affecting its physical properties at multiple spatial scales (see Slane et al. 2016, for a review). Mass, energy and momentum are transferred to the nearby material during the adiabatic phase, also known as Sedov-Taylor phase (Taylor 1950; Sedov 1959), during which the energy dissipation is due to expansion and radiative losses are

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negligible (Chevalier 1974; Cioffi et al. 1988; Blondin et al. 1998; Kim & Ostriker 2015; Martizzi et al. 2015).

At galactic scales, Supernova remnants (SNRs) drive mass-loaded winds that can displace the molecular material, delaying its conversion into stars and hence suppressing star formation in galaxies (Bigiel et al. 2008, 2010; Krumholz et al. 2012; Leroy et al. 2013). This is known as *negative feedback* (Kruijssen et al. 2019; Körtgen et al. 2016). At the same time, the shock compression of surrounding molecular gas by expanding SNRs can locally (spatial scales  $<10$  pc) enhance the density of the molecular material, increase the gas turbulence and eventually trigger the formation of new stars (Inutsuka et al. 2015; Klessen & Glover 2016). This effect is known as *positive feedback*. The interplay and relative dominance between positive and negative feedback may depend on several conditions, e.g., the density and gas distribution of the processed material, the evolutionary stage of SNRs (Shima et al. 2017) and it is paramount in regulating the star formation efficiency and time evolution of galaxies (Bigiel et al. 2008, 2010; Scannapieco et al. 2008; Leroy et al. 2013; Heckman & Thompson 2017). Indeed, it is essential to include stellar feedback in numerical simulations of galactic disc evolution to predict star formation rate and stellar masses comparable to those measured in the ISM (Hennebelle & Iffrig 2014; Smith et al. 2018; Marinacci et al. 2019).

Over time, galaxy evolution simulations have adopted different ad hoc approaches to include SNRs feedback. Early low spatial resolution models treated SN feedback by manually injecting energy into the system at once (for an overview, see Ceverino & Klypin 2009). Such an approach did not consider the Sedov-Taylor phase and as a result, all the injected energy was quickly radiated away with no effects on the ISM (Katz 1992). In order to overcome this problem and force the adiabatic phase to occur, later works introduced an artificial delay in the radiative cooling, either by redistributing the injected energy both in space and time (Dalla Vecchia & Schaye 2012) or by switching it off for a certain length of time (Stinson et al. 2006; Governato et al. 2010; Agertz et al. 2011; Teyssier et al. 2013). Alternatively to these "delaying cooling" methods, other works treat SN feedback as mechanical feedback and introduce the SNRs at a certain time, with a certain radius and by turning on their kinetic energy and momentum in an ad hoc manner (Dubois & Teyssier 2008; Kimm & Cen 2014; Martizzi et al. 2016). Recent high-resolution simulations within the Feedback In Realistic Environments (FIRE) project are in the process of implementing self-consistently the treatment of SN feedback in galaxy evolution models (e.g., Wetzel et al. 2016; Sanderson et al. 2018). These works resolve in space and time the different SN evolutionary stages and the different structures of the ISM, limiting the use of sub-resolution approximations for feedback processes (Hopkins et al. 2014). Finally, extensive theoretical studies focused on the impact of SN-driven feedback onto the dense molecular material of the ISM have been reported by e.g. Padoan et al. (2016, 2017) and Seifried et al. (2020).

In light of all these extensive theoretical works, current models are able to efficiently describe the expansion of SNRs in a single and/or multi-phase ISM and to make predictions on the energy and momentum imprinted on the nearby material (Koo et al. 2020). However, such predictions are still to be fully validated from an observational point of view. In particular, it remains to be constrained the amount of momentum and energy injected by SNRs into the molecular phase of the ISM i.e., the material that primarily fuels star formation in galaxies. This can be efficiently done by studying the emission of those molecular species that trace the high-density shocked gas and whose mm and sub-mm emission is enhanced

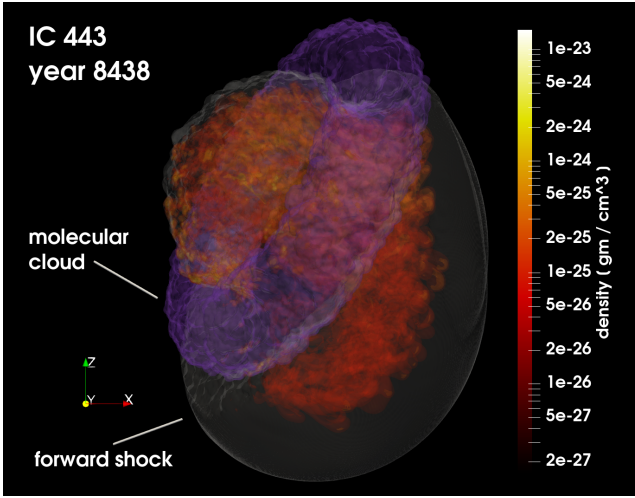
in sites of SNR-cloud interactions (e.g., Neufeld et al. 2007). Among these species, Silicon Monoxide (SiO) is a unique tracer of dense and shocked molecular material (critical density  $n_{crit} > 10^5$  cm $^{-3}$ ). Indeed, SiO appears heavily depleted in quiescent regions ( $\chi \sim 10^{-12}$ ; Martin-Pintado et al. 1992; Jiménez-Serra et al. 2005) but its abundances can be enhanced by up to a factor  $\sim 10^6$  in regions where the shock propagation causes the sputtering of dust grains or grain-grain collisions. Here, Si is released into the gas phase and SiO is quickly formed (Caselli et al. 1997; Schilke et al. 1997; Jiménez-Serra et al. 2008; Gusdorf et al. 2008). SiO emission triggered by SNR shocks has been detected toward W51 (Dumas et al. 2014) and W28 (Vaupre 2015), as part of multi-line studies aimed to infer cosmic ray enhancement in SNRs. More recently, in Cosentino et al. (2019), we have reported a dedicated study of the SiO emission arising from the shock interaction between the SNR W44 and the molecular cloud G034.77-00.55 (thereafter G034). Toward this source, the molecular gas pushed away by the expansion of the SNR is interacting with the pre-existing massive molecular cloud, causing a parsec-scale shock seen with relatively narrow SiO emission ( $<3$  km s $^{-1}$ ). The shock is propagating at a velocity of  $\sim 23$  km s $^{-1}$  and is compressing the gas to densities  $n(\text{H}_2) > 10^5$  cm $^{-3}$  (Cosentino et al. 2019). The momentum injected into the dense shocked gas is estimated to be  $\sim 20 M_\odot$  km s $^{-1}$  (Cosentino et al. 2019).

In order to extend the literature sample of SNR-cloud interaction sites seen in SiO emission, we have initiated the ESO-ARO Public Spectroscopic Survey "SHock interactions between supernova REmnants and molecular Clouds" i.e., SHREC, an ongoing large (800 hours) observing program using the 12m antenna at the Arizona Radio Observatory (ARO). SHREC aims to identify sites of ongoing SNR-cloud interaction by mapping the SiO(2-1), H $^{13}$ CO $^+(1-0)$  and HN $^{13}$ C(1-0) emission toward a sample of 27 SNRs. These sources have been selected for being relatively nearby (kinematic distance  $\leq 6$  kpc) and for showing evidence of interaction with the surrounding molecular material (Ferrand & Safi-Harb 2012; Green 2019). This includes enhanced X-ray emission, the presence of OH maser emission at 1720 MHz and enhanced CO(2-1)/CO(1-0) ratios (Slane et al. 2016). The final goal of SHREC is to identify sites of large-scale interactions driven by SNRs and to investigate how these affect the star formation potential and dispersal of the surrounding molecular material. The technical presentation of the project and first data release will be presented in a forthcoming paper (Cosentino et al. in prep).

## 1.1 The SNR IC443

As part of SHREC, we have obtained SiO(2-1) and H $^{13}$ CO $^+(1-0)$  emission maps toward the well-known source G189.1+3.0, also known as IC443. IC443 is a mixed-morphology SNR, i.e., with a shell-like morphology in the radio wavelengths and centrally filled in the X-rays (Rho & Petre 1998). The source is located at a distance of  $\sim 1.9$  kpc (Ambrocio-Cruz et al. 2017) and its age estimate is highly uncertain. Although a typical age of  $\sim 30000$  years is usually assumed (Chevalier 1999), recent simulations suggest that the SNR could be much younger i.e.,  $\sim 3000$ -8000 years (Troja et al. 2008; Ustamujic et al. 2021).

The IC443 shell is known to be expanding into an atomic cloud in the north-east (Denoyer 1979) and into a molecular cloud in the north-west to south-east direction (Cornett et al. 1977). The first map of the Giant Molecular Cloud surrounding the SNR was reported by Cornett et al. (1977) by means of CO(1-0) emission. Later on,



**Figure 1.** Three-dimensional structure of IC443 derived with a hydrodynamic model that reproduces the morphology of the remnant and the distribution of ejecta (Ustamujic et al. 2021). The volume rendering that uses the red colour palette (colour coding on the right of the panel) shows the distribution of ejecta approximately 8400 years after the supernova explosion. The semi-transparent grey outer surface marks the position of the forward shock. The semi-transparent toroidal structure in purple represents the molecular cloud with which the blast wave of the remnant is interacting. The Earth vantage point lies on the negative y-axis i.e., the perspective is in the plane of the sky.

Denoyer (1979) and Huang & Thaddeus (1986) identified four major sites of interaction between IC443 and the cloud, named clumps A, B, C and G. By using XMM-Newton maps of the X-ray emission associated with the SNR, Troja et al. (2006) reported a geometry of the SNR-cloud system consistent with that of a toroidal molecular cloud wrapped around the expanding SNR and tilted by  $\sim 50^\circ$  with respect to the equatorial mid-plane. The three-dimensional structure of the cloud-SNR system is reported in Figure 1, as derived with the hydrodynamic model presented by Ustamujic et al. (2021). In the geometry presented in Figure 1, clump G corresponds to the part of the torus that is located in the foreground, between the observer and the expanding shell. Among the identified sites, clump G shows the strongest evidence of ongoing shock interaction, i.e., the presence of OH maser emission (e.g. Hewitt et al. 2006), shocked material probed by multi-transitions CO gas (e.g. Zhang et al. 2010; Dell’Ova et al. 2020), localised non-thermal X-ray emission (e.g. Petre et al. 1988; Bocchino & Bykov 2000) and shock-excited  $H_2$  emission (e.g., Reach et al. 2019). Previous 3mm line survey studies indicated the presence of SiO(2-1) emission toward the clump (Ziurys et al. 1989; van Dishoeck et al. 1993). In this paper, we present extended maps of the SiO(1-0), SiO(2-1) and  $H^{13}CO^+(1-0)$  emission toward the molecular clump G. We have used the early results of the SHREC large program to study the mass-energy-momentum injection and density enhancement induced by IC443 onto clump G. With this work, we aim to provide a direct estimate of the impact of SN feedback on the molecular phase of the ISM. The paper is organised as follows. In Section 2, we present the observing method and data acquisition. In Section 3, we present the result of the analysis performed for the SiO and  $H^{13}CO^+$  emission toward clump G. Finally, in Sections 4 and 5 we discuss our findings and present our conclusions.

## 2 OBSERVATIONS

Maps of the SiO(2-1) (86.8469 GHz),  $H^{13}CO^+(1-0)$  (86.7543 GHz) and  $HN^{13}C(1-0)$  (87.0909 GHz) emission toward clump G were obtained in June 2020 as part of SHREC (P.I. Giuliana Cosentino). Observations were performed using the 12m antenna of the Arizona Radio Observatory (Kitt Peak, Arizona, USA) in on-the-fly (OTF) mode, with scanning speed of  $30''/\text{sec}$  and map size of  $10' \times 10'$ . The map central coordinates are  $RA=06^h 16^m 32^s$ ,  $Dec=22^\circ 30' 45''$ . The AROWS receiver was used with tuning frequency 89.2 GHz and spectral resolution of 78 kHz ( $\sim 0.3 \text{ km s}^{-1}$  at 86 GHz), providing a bandwidth of 500 MHz.

In November 2020, we used the 40m antenna at the Yebes Observatory (Castilla-La Mancha, Spain) to obtain complementary SiO(1-0) (43.4238 GHz) maps (project code 20B009). The SiO(1-0) observations were performed in OTF mode with scanning speed  $15''/\text{sec}$ , central coordinates  $RA=06^h 16^m 42.4^s$ ,  $Dec=22^\circ 32' 26.3''$  and map size  $3.5' \times 3.5'$ , corresponding to the full extension of the SiO(2-1) emission. We used the FFT spectrometer in Q band (tuning frequency 43.424 GHz), with spectral resolution of 38 kHz ( $\sim 0.3 \text{ km s}^{-1}$  at 43 GHz) and bandwidth 2.5 GHz.

For both sets of observations, we use the reference position  $RA=06^h 19^m 01^s$ ,  $Dec=22^\circ 28' 11''$ . Intensities were measured in units of antenna temperature and converted into main-beam brightness temperatures using beam efficiencies of 0.61 and 0.52, for the ARO and Yebes observations, respectively. The final data cubes were generated using the GILDAS<sup>1</sup> package and have beam-sizes of  $45''$  and  $76''$ , for the Yebes and ARO maps, respectively and a common spectral resolution of  $0.5 \text{ km s}^{-1}$ . The achieved root-mean-square (rms) per channel and per beam is of 10 mK for the Yebes maps and 30 mK for the ARO maps. We note that the  $HN^{13}C(1-0)$  emission observed as part of SHREC is found to be below the  $3 \times \text{rms}$  level across the full map and hence we do not include it in the following analysis.

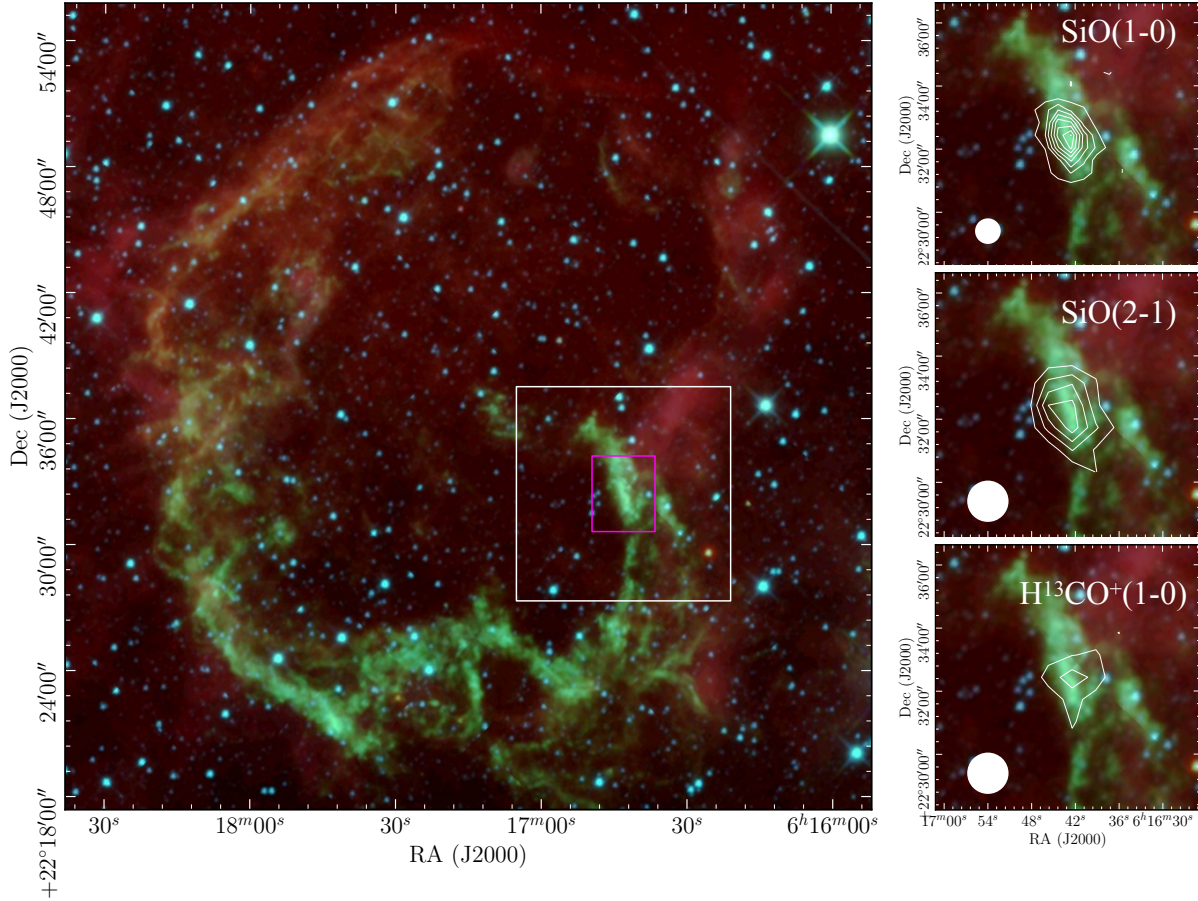
## 3 RESULTS

### 3.1 Morphology and Kinematics of the Shocked Gas

In Figure 2, we present the 3-colour image of the SNR IC443 (left) obtained as part of the WISE all-sky survey (Wright et al. 2010) together with the integrated (in velocity) intensity maps (right) of the SiO(1-0) (top), SiO(2-1) (middle) and  $H^{13}CO^+(1-0)$  (bottom) emission. The shocked and dense gas emission is coincident with a bright and extended  $4.5 \mu\text{m}$  ridge, a signature of shock-excited gas (Noriega-Crespo et al. 2004) and tracing the SNR shock front. The shocked gas tracer emission shows a morphology that is localised with respect to the  $4.5 \mu\text{m}$  ridge and elongated in the same direction. Such an emission extends  $>3 \times$  the beam-aperture ( $\sim 0.4$  and  $\sim 0.6 \text{ pc}$  for Yebes and ARO observations, respectively) and over parsec scales i.e.  $\sim 1.8 \times 1.6 \text{ pc}^2$ . The  $H^{13}CO^+$  emission also extends over a parsec scale ( $1.2 \times 1.3 \text{ pc}^2$ ) but it appears to be more compact than the SiO emission, i.e.,  $<2 \times$  the beam-aperture.

In Figure 3, we report the moment 1 velocity map (colour scale) obtained for the SiO(1-0), superimposed on the SiO(1-0) integrated intensity emission contours (black). As seen from Figure 3, the SiO emission shows a velocity gradient, with the blue-shifted gas located toward the east-southeast and the red-shifted emission found toward the west-northwest. Moving away from the  $4.5 \mu\text{m}$  ridge and into the

<sup>1</sup> <https://www.iram.fr/IRAMFR/GILDAS>



**Figure 2.** Left: Three-colour image (red= 22  $\mu\text{m}$ ; green = 4.6  $\mu\text{m}$ ; blue = 3.4  $\mu\text{m}$ ) of the SNR IC443 (WISE all-sky survey [Wright et al. 2010](#)). White and magenta rectangles indicate the extent of the ARO and Yebeas maps respectively. Right: Integrated intensity maps (-22; 6  $\text{km s}^{-1}$ ) of the SiO(1-0) (top;  $\sigma=0.1$   $\text{K km s}^{-1}$ ), SiO(2-1) (middle;  $\sigma=0.2$   $\text{K km s}^{-1}$ ) and  $\text{H}^{13}\text{CO}^+(1-0)$  (bottom;  $\sigma=0.2$   $\text{K km s}^{-1}$ ) are shown in white contours (from  $3\sigma$  in steps of  $3\sigma$ ). The ARO and Yebeas beam sizes are shown as white circles in the bottom left of each panel.

SNR, the SiO velocity is systematically blue-shifted with respect to the central velocity of IC443 i.e.  $-4.5 \text{ km s}^{-1}$ , estimated by means of  $^{12}\text{CO}$  and  $\text{HCO}^+$  observations ([White et al. 1987](#); [Dickman et al. 1992](#); [van Dishoeck et al. 1993](#)).

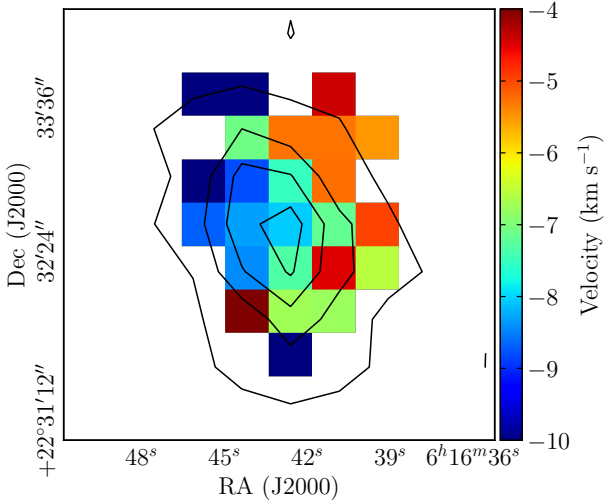
### 3.2 Excitation Conditions of the Shocked Gas

We now consider the SiO(1-0) and (2-1) line intensities to infer the excitation conditions of the shocked gas, i.e.,  $\text{H}_2$  number density,  $n(\text{H}_2)$ , SiO column density,  $N(\text{SiO})$ , excitation temperature,  $T_{\text{ex}}$  and how these vary as a function of the gas velocity. For this analysis, the SiO(1-0) emission cube has been spatially smoothed to the same angular resolution of the SiO(2-1) and  $\text{H}^{13}\text{CO}^+(1-0)$  maps and all cubes were spectrally smoothed to a velocity resolution of  $2 \text{ km s}^{-1}$ . The SiO(1-0) (black), SiO(2-1) (red) and  $\text{H}^{13}\text{CO}^+$  (green) spectra obtained by averaging the emission from pixels with signal above  $3\sigma$  are shown in Figure 4, along with their respective  $3\times\text{rms}$  levels (dotted horizontal lines).

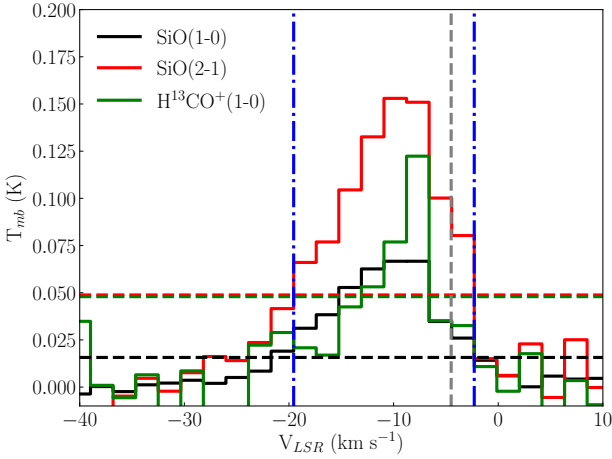
From Figure 4, the SiO(1-0) and SiO(2-1) emission show significant intensities ( $>3\times\text{rms}$ ) for velocity channels in the range  $-19.5$ – $-2.5 \text{ km s}^{-1}$  (vertical blue dotted dashed lines). We have therefore limited our analysis to these velocities. For each of the considered velocity

channels, we have measured the SiO(1-0) and SiO(2-1) line intensity in unit of K (Table 1) and used the non-LTE radiative transfer code RADEX ([van der Tak et al. 2007](#)) to estimate the physical conditions that best reproduce the line strength. RADEX uses the Large Velocity Gradient (LVG) approximation ([Sobolev 1957](#)) to predict line intensities of specific molecules in homogeneous interstellar clouds, starting from a pre-defined system geometry and five input parameters. These are the gas kinetic temperature,  $T_{\text{kin}}$ , the temperature of the background material,  $T_{\text{bg}}$ , the volume density of the collisional partners, the molecule column density,  $N(\text{SiO})$  and the width of emission line. The RADEX output provides the user with line strengths at several frequencies for the selected molecule as well as excitation temperatures and optical depth estimates for each transition. For our analysis, we have assumed a geometry consistent with that of a slab of material processed by a shock. In addition, we have used  $\text{H}_2$  as collisional partner and specified the  $\text{H}_2$  volume density,  $n(\text{H}_2)$ , as input parameter. The collisional coefficients between  $\text{H}_2$  and SiO were extracted from the LAMDA database<sup>2</sup> for the first 30 SiO rotational levels ([Balança et al. 2018](#)). We have assumed

<sup>2</sup> <https://home.strw.leidenuniv.nl/moldata/SiO.html>



**Figure 3.** SiO(1-0) moment 1 velocity map (colour scale) toward IC443 superimposed on the SiO(1-0) integrated intensity map contours (black) from  $3\sigma$  by steps of  $6\sigma$  ( $\sigma=0.1$  K km s $^{-1}$ ).



**Figure 4.** SiO(1-0) (black), SiO(2-1) (red) and H $^{13}$ CO $^{+}$ (1-0) (green) spectra extracted toward the regions of the map with emission above the  $3\sigma$  levels. The horizontal dashed lines indicate the  $3\times$  rms levels for each species. Vertical blue dashed dotted lines indicated the velocity range considered for the comparison with RADEX models. Finally, the vertical grey line indicates the central velocity of IC443.

background temperature  $T_{bg}=2.73$  K consistent with the Cosmic Microwave Background emission and used a width of the line of 2 km s $^{-1}$ , corresponding to the velocity width of each channel. Since only two SiO rotational transitions are here observed, it is not possible to constrain at the same time the three remaining parameters,  $n(\text{H}_2)$ ,  $N(\text{SiO})$  and  $T_{kin}$ . Therefore, in the following analysis we proceed by assuming a certain value of  $T_{kin}$  and investigate the sensitivity of our results with respect this assumption. In Figure 5, we show multiple grids of RADEX models obtained for  $n(\text{H}_2)$  in the range  $10^2$ - $10^9$

cm $^{-3}$ ,  $N(\text{SiO})$  in the range  $10^9$ - $10^{16}$  cm $^{-2}$  and with fixed  $T_{kin}$  of 10 K, 20 K, 50 K and 100 K.

As shown in Figure 5, the excitation temperature of the SiO(1-0) transition varies significantly for different values of kinetic temperature. In particular, already at  $T_{kin}>20$  K, RADEX predicts negative excitation temperatures for the SiO(1-0) emission i.e., the SiO(1-0) emission is predicted to behave as a maser. SiO(1-0) maser emission is commonly detected toward different objects e.g., variable stars (Cho et al. 2007), massive young stellar objects (Issaoun et al. 2017), massive star clusters (Verheyen et al. 2012), but the rotational transition is usually observed to also be vibrationally excited. At the best of our knowledge, the vibrational ground state of SiO J=1-0 here analysed has been observed with characteristics typical of maser emission only toward evolved stars (Boboltz & Claussen 2004). Toward these objects, the transition shows brightness temperatures  $>10^3$  K, much higher than the intensities here observed, and is usually detected simultaneously to higher vibrational transitions at close frequencies ( $\sim 43.1$  GHz). Such frequencies are covered by the bandwidth of our Yebes observations but no vibrationally excited emission are detected. We therefore conclude that the SiO(1-0) emission here reported does not show characteristics typical of maser emission and assume  $T_{kin}=15$  K in the following analysis. Our assumption of  $T_{kin} < 20$  K reproduces well the observed excitation of the SiO line emission and exclude the possibility that  $T_{ex}<0$  K (maser effects). We also note that the assumed  $T_{kin}$  is consistent with that estimated for the shocked CO emission by Dell’Ova et al. (2020) and only a factor of 2 lower than that reported by Ziurys et al. (1989), using multiple Ammonia (NH $_3$ ) transitions ( $T_{kin} \sim 33$  K).

Our final grid consists of 250000 models with  $n(\text{H}_2)$  in the range  $\sim 10^2$ - $10^7$  cm $^{-3}$  and  $N(\text{SiO})$  in the range  $\sim 10^9$ - $10^{16}$  cm $^{-2}$ ,  $T_{kin}=15$  K,  $T_{bg}=2.73$  K and linewidth=2 km s $^{-1}$ . The Si(1-0) line intensities,  $I_{(1-0)}$  (left panel), and the SiO(2-1)/SiO(1-0) line intensity ratios,  $I_{(2-1)}/I_{(1-0)}$  (right panel), predicted by our grid of models are shown in Figure 6.

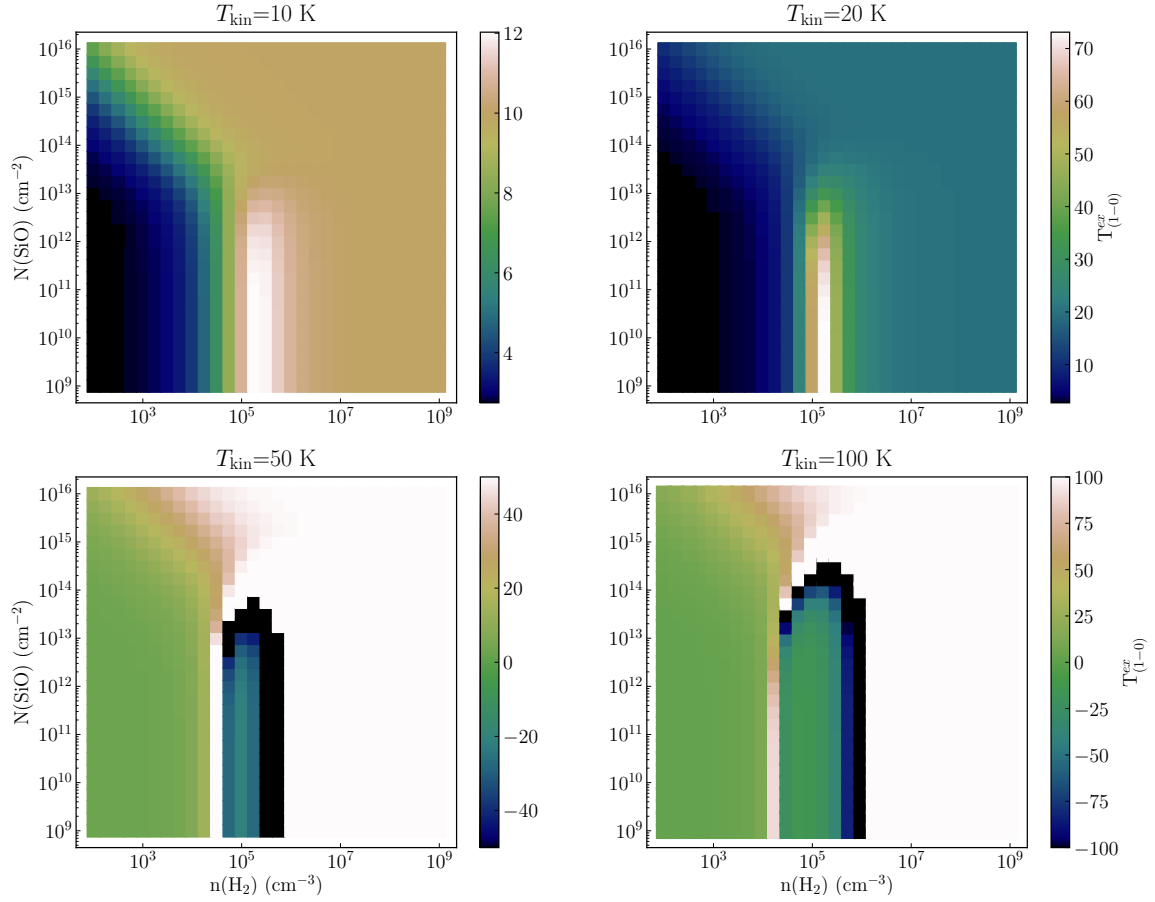
For each of the considered velocity channels, we have compared the measured SiO(1-0) and (2-1) intensities with those predicted by all models in the grid and computed the associated chi square,  $\chi^2$ , according to the following:

$$\chi^2 = \left[ \frac{(I_{1-0} - I_{RAD})^2}{(\Delta I_{1-0})^2} + \frac{(I_{2-1} - I_{RAD})^2}{(\Delta I_{2-1})^2} \right], \quad (1)$$

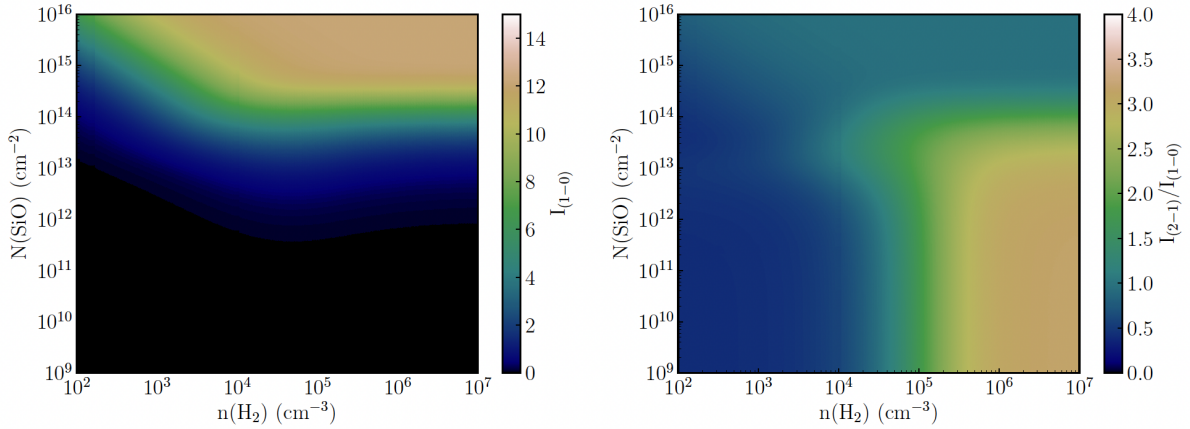
where,  $I_{1-0}$  and  $I_{2-1}$  are the observed intensities of the SiO(1-0) and (2-1) lines and the subscripts RAD indicates the corresponding quantities estimated by RADEX. For each pair of intensity values, the uncertainty is estimated as the rms per channel, i.e., 5 mK and 15 mK for SiO(1-0) and SiO(2-1), respectively.

For each velocity channel, we have extracted a best model as the one that minimises the  $\chi^2$  and a range of best RADEX models as those for which  $\chi^2<1$ . The obtained best values and ranges are reported in Table 1, along with the central velocity of the channel and the measured SiO intensities. Since only one transition has been observed for H $^{13}$ CO $^{+}$ , a similar analysis is not possible for this dense gas tracer. Hence, we have assumed H $^{13}$ CO $^{+}$ (1-0) to have excitation temperatures similar to that estimated for SiO(2-1) and used the best RADEX values at each velocity step to estimate the H $^{13}$ CO $^{+}$  column density. This is justified by the fact that the SiO(2-1) and H $^{13}$ CO $^{+}$ (1-0) transitions have a similar critical density. The obtained values are reported in column 9 of Table 1.

In Figure 7, the best values (dot markers) and acceptable ranges (vertical lines) obtained for the  $n(\text{H}_2)$  (right panel),  $N(\text{SiO})$  (middle panel) and  $T_{ex}$  (left panel) are shown along with the SiO(1-0) (black)



**Figure 5.** Grids of RADEX models obtained for  $n(\text{H}_2)$  in the range  $10^2$ - $10^9 \text{ cm}^{-3}$ ,  $N(\text{SiO})$  in the range  $10^9$ - $10^{16} \text{ cm}^{-2}$  and  $T_{\text{kin}}$  of 10 K (top left), 20 K (top right), 50 K (bottom left) and 100 K (bottom right). For each set of  $N(\text{H}_2)$ ,  $N(\text{SiO})$  and  $T_{\text{kin}}$ , the  $T_{\text{ex}}$  predicted for the SiO(1-0) transition is shown in color scales. Although here not shown for simplicity, the  $T_{\text{ex}}$  of the SiO(2-1) transitions shows similar trends as a function of kinetic temperature.



**Figure 6.** SiO(1-0) line intensities,  $I_{(1-0)}$  (left), and SiO(2-1)/SiO(1-0) line intensity ratios,  $I_{(2-1)}/I_{(1-0)}$  (right) as predicted by the final grid of model obtained for  $T_{\text{kin}}=15 \text{ K}$ .

and SiO(2-1) (red) spectra. From Figure 7, the  $n(\text{H}_2)$  decreases from red- to blue-shifted velocities. For  $V_{LSR} > -5 \text{ km s}^{-1}$ , the volume density is  $> 5 \times 10^5 \text{ cm}^{-3}$ , while for  $V < -5 \text{ km s}^{-1}$ , the volume density decreases and sets on a relatively constant value ( $\sim 1.5 \times 10^5 \text{ cm}^{-3}$ ). A similar trend is observed for the SiO excitation temperatures (right panel), where the two distributions hint to a higher excitation of the gas at red-shifted velocities, i.e., where the  $T_{\text{ex}}^{2-1}$  increases and the  $T_{\text{ex}}^{1-0}$  decreases.

From the right panel in Figure 7, the  $T_{\text{ex}}$  estimated for the SiO(1-0) transition is  $> 15 \text{ K}$  at all velocities, i.e., higher than the kinetic temperatures assumed in our models. This *supra-thermal* excitation is a known behaviour, typically observed for linear molecules and at densities consistent with the critical density ( $n_{\text{crit}} \sim 4 \times 10^4 \text{ cm}^{-3}$  for the J=1-0 SiO transition). Depending on the  $\text{H}_2$  and SiO number densities, the radiative and collisional excitation of the SiO compete and LTE conditions are expected to be achieved when collisional excitation dominates. Hence, the  $T_{\text{ex}}$  is expected to be at most equal to  $T_{\text{kin}}$ . However, due to quantum selection rules, radiative transitions in linear molecules only occur between successive rotational levels ( $\Delta J = \pm 1$ ). Furthermore, the Einstein coefficient A, describing spontaneous radiative decay, increases with the J of the transition. As a consequence of these two effects, higher J-levels will be de-excited faster than the low J-levels, causing a supra-population of the low-J states, and resulting in  $T_{\text{ex}}$  rising above the LTE value. Such behaviour is analysed in details by Koeppen & Kegel (1980) for the CO molecule.

### 3.3 Energy, Mass and Momentum

As last step in our analysis, we have estimated the mass (M), momentum (P) and kinetic energy (E) of the SiO and  $\text{H}^{13}\text{CO}^+$  emission, using the method described in Dierickx et al. (2015):

$$M = \frac{d^2}{\chi(\text{mol})} \times \mu_g m(\text{H}_2) \times \Sigma_{\text{pix}} N(\text{mol})_{\text{pix}}, \quad (2)$$

$$P = MV, \quad (3)$$

$$E = \frac{1}{2} MV^2, \quad (4)$$

where d is the source kinematic distance (1.9 kpc; Ambrocio-Cruz et al. 2017),  $\mu_g = 1.36$  is the gas molecular weight,  $m(\text{H}_2)$  is the molecular hydrogen mass,  $\chi(\text{mol})$  is the fractional abundance with respect to  $\text{H}_2$  and  $\Sigma_{\text{pix}} N(\text{mol})_{\text{pix}}$  is the total column density of the molecule, summed for all pixels with signal above  $3\sigma$ . Finally, V is the line width at the base ( $3 \times \text{rms}$ ) of the emission. Similarly to what described in Cosentino et al. (2018), we have obtained an estimate of the  $\chi(\text{SiO})$  by considering the following equation:

$$\chi(\text{SiO}) = \frac{N(\text{SiO})}{N(\text{H}^{13}\text{CO}^+)} \times \chi(\text{HCO}^+) \times \frac{^{13}\text{C}}{^{12}\text{C}}, \quad (5)$$

where  $N(\text{SiO}) \sim (3.3 \pm 0.5) \times 10^{12} \text{ cm}^{-2}$  and  $N(\text{H}^{13}\text{CO}^+) \sim (7 \pm 1) \times 10^{11} \text{ cm}^{-2}$  have been obtained by summing the values reported in Table 1. The corresponding uncertainties have been obtained by considering the  $N(\text{SiO})$  variability ranges in Table 1 and by assuming that both the SiO and  $\text{H}^{13}\text{CO}^+$  column densities have the same relative error. Hence, we have assumed  $^{12}\text{C}/^{13}\text{C} \sim 50 \pm 10$  i.e., we have assigned a 20% uncertainty (e.g. Zeng et al. 2017). We note that the assumed  $^{12}\text{C}/^{13}\text{C}$  value is consistent with that reported

by Dell'Ova et al. (2020), toward clump G. Finally, we assume  $\chi(\text{HCO}^+) \sim (1 \pm 0.5) \times 10^{-8}$ , as reported by van Dishoeck et al. (1993). We thus estimated the SiO and  $\text{H}^{13}\text{CO}^+$  abundances with respect to  $\text{H}_2$  to be  $\chi(\text{SiO}) \sim (1 \pm 0.5) \times 10^{-9}$  and  $\chi(\text{H}^{13}\text{CO}^+) \sim (2 \pm 1) \times 10^{-10}$ .

In order to estimate the SiO and  $\text{H}^{13}\text{CO}^+$  column densities at each pixel, we have assumed  $T_{\text{ex}} \sim 10 \text{ K}$  for both species, obtained as the average of the values reported in Table 1 for SiO(2-1). Hence, we use the  $\text{H}^{13}\text{CO}^+(1-0)$  and SiO(2-1) transitions to estimate the energy, mass and momentum of the dense and shocked gas, respectively. As reported in Table 2, we obtain  $M \sim 125 \pm 50$  and  $100 \pm 60 \text{ M}_{\odot}$ ,  $P \sim (8 \pm 3) \times 10^2$  and  $P \sim (2 \pm 1) \times 10^3 \text{ M}_{\odot} \text{ km s}^{-1}$  and  $E \sim (4.5 \pm 1.8) \times 10^{40}$  and  $\sim (2.6 \pm 1.6) \times 10^{41} \text{ ergs}$  for  $\text{H}^{13}\text{CO}^+$  and SiO, respectively. The uncertainties have been obtained by following the standard propagation rules.

## 4 DISCUSSION

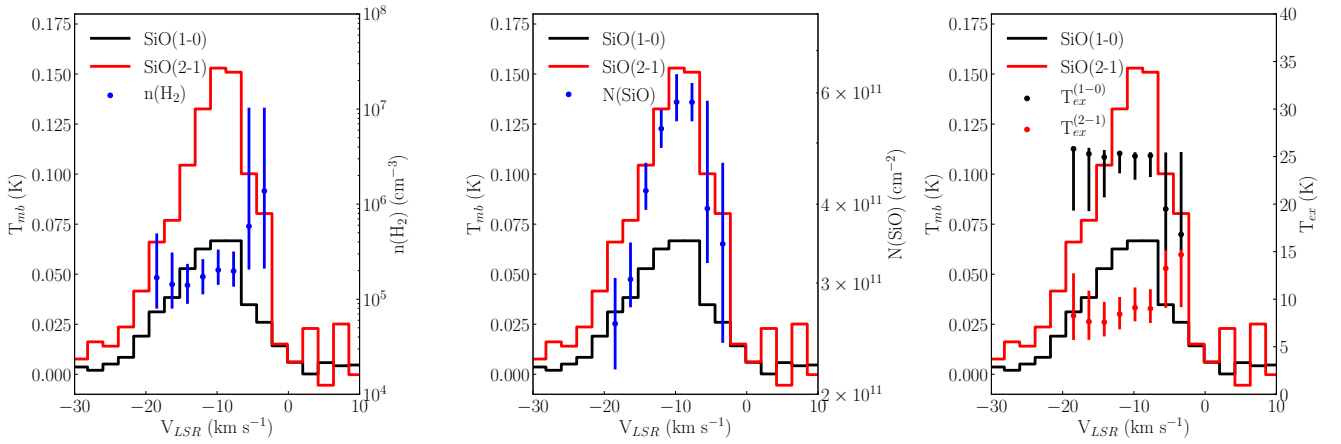
### 4.1 Can the SiO emission be due to molecular outflows powered by embedded protostars?

The shock interaction between IC443 and clump G has been largely investigated from both an observational (e.g. Ziurys et al. 1989; Dickman et al. 1992; van Dishoeck et al. 1993; Reach et al. 2019; Dell'Ova et al. 2020; Kokusho et al. 2020) and theoretical (e.g. Troja et al. 2006, 2008; Ustamujic et al. 2021) point of view. However, SiO is usually widely observed in regions of ongoing star formation activity (e.g., Codella et al. 2007; López-Sepulcre et al. 2011; Liu et al. 2020). Hence, we now discuss the possibility that the SiO emission observed toward clump G may be due to molecular outflows driven by deeply embedded protostars.

As reported in Table 2, the energy measured for the shocked gas is  $\sim 2.6 \times 10^{41} \text{ ergs}$ . This is several orders of magnitudes lower than the typical kinetic energy measured for molecular outflows powered by high-mass protostars i.e.,  $\sim 10^{46} \text{ ergs}$  (e.g., Zhang et al. 2005; López-Sepulcre et al. 2009) and intermediate-mass protostars i.e.,  $\sim 10^{43}$ - $10^{44} \text{ ergs}$  (e.g., Beltrán et al. 2006, 2008). We therefore exclude the possibility that ongoing high-mass and intermediate-mass star formation may be driving the observed SiO emission. On the other hand, Dell'Ova et al. (2020) reported the presence of  $\sim 25$  Young Stellar Objects (YSOs) spatially associated with the shocked gas in clump G and located within a distance of  $\pm 500 \text{ pc}$  (see Figure 14 in Dell'Ova et al. 2020). We now assume that the SiO emission is entirely due to putative outflows powered by these 25 YSOs, and that each source contributes equally to the final SiO emission. In this scenario, each outflow should have on average a mass of  $M_{\text{SiO}}/25 \sim 4 \text{ M}_{\odot}$  and a momentum of  $P_{\text{SiO}}/25 \sim 80 \text{ M}_{\odot} \text{ km s}^{-1}$ . These estimates are several orders of magnitude higher than those typically measured toward molecular outflows driven by low-mass protostars i.e.,  $M \sim 0.005$ – $0.15 \text{ M}_{\odot}$ ,  $P \sim 0.004$ – $0.12 \text{ M}_{\odot} \text{ km s}^{-1}$  (e.g., Dunham et al. 2014). This is even more stringent if we consider the more likely scenario in which only few of the 25 YSOs are effectively driving outflows and thus contributing to the observed SiO emission. Hence, although we cannot exclude that a small contribution to the observed SiO emission may be due to molecular outflows powered by low-mass protostars, the major contribution to the observed SiO emission likely arises from the large-scale shock interaction occurring between IC443 and clump G.

**Table 1.** Results of the RADEX analysis performed for the SiO and  $\text{H}^{13}\text{CO}^+$  emission. For each velocity channel, the central velocity, the SiO(1-0), SiO(2-1) and  $\text{H}^{13}\text{CO}^+$ (1-0) intensities, the best  $n(\text{H}_2)$ ,  $N(\text{SiO})$ , and  $T_{\text{ex}}$  values and ranges are reported. We note that all the measured  $\text{H}^{13}\text{CO}^+$  intensities are at least higher than  $1 \times$  the corresponding rms of 15 mK.

| V<br>(km s <sup>-1</sup> ) | I <sub>1-0</sub><br>(K) | I <sub>2-1</sub><br>(K) | $n(\text{H}_2)$<br>( $\times 10^5 \text{ cm}^{-3}$ ) | $N(\text{SiO})$<br>( $\times 10^{11} \text{ cm}^{-2}$ ) | $T_{\text{ex}}^{1-0}$<br>(K) | $T_{\text{ex}}^{2-1}$<br>(K) | $I_{\text{H}^{13}\text{CO}^+}$<br>(K) | $N(\text{H}^{13}\text{CO}^+)$<br>( $\times 10^{10} \text{ cm}^{-2}$ ) |
|----------------------------|-------------------------|-------------------------|--|---|------------------------------|------------------------------|---------------------------------------|---|
| -18.5                      | 0.031                   | 0.066                   | 1.7 (0.8-4.8)  | 2.6 (2.2-3.0)   | 26 (20-26)                   | 8 (6-13)                     | 0.020                                 | 3.5   |
| -16.5                      | 0.038                   | 0.077                   | 1.4 (0.8-3.0)  | 3.0 (2.8-3.5)   | 25 (19-26)                   | 8 (6-11)                     | 0.017                                 | 3.0   |
| -14.5                      | 0.053                   | 0.104                   | 1.4 (0.9-2.3)  | 4.2 (3.9-4.6)   | 25 (21-26)                   | 8 (6-10)                     | 0.043                                 | 7.0   |
| -12.5                      | 0.063                   | 0.133                   | 1.7 (1.2-2.6)  | 5.3 (4.9-5.6)   | 25 (23-25)                   | 8 (7-10)                     | 0.053                                 | 9.5   |
| -9.5                       | 0.067                   | 0.153                   | 2.0 (1.5-3.2)  | 5.8 (5.4-6.4)   | 25 (23-25)                   | 9 (8-11)                     | 0.077                                 | 13  |
| -7.5                       | 0.067                   | 0.151                   | 2.0 (1.4-3.1)  | 5.8 (5.4-6.2)   | 25 (23-25)                   | 9 (8-11)                     | 0.122                                 | 22  |
| -5.5                       | 0.035                   | 0.100                   | 5.9 (2.1-100)  | 3.9 (3.2-5.8)   | 20 (15-25)                   | 13 (9-15)                    | 0.035                                 | 6.5   |
| -3.5                       | 0.026                   | 0.080                   | 13.8 (2.2-100)                                       | 3.5 (2.4-4.6)   | 17 (15-25)                   | 15 (9-15)                    | 0.033                                 | 6.3   |



**Figure 7.** SiO(1-0) (black) and SiO(2-1) (red) spectra as shown in Figure 2 and with superimposed the best values (dot markers) and ranges (vertical lines) obtained for  $n(\text{H}_2)$  (blue, left panel),  $N(\text{SiO})$  (blue, middle panel) and the two excitation temperatures  $T_{\text{ex}}^{1-0}$  (black, right panel) and  $T_{\text{ex}}^{2-1}$  (red, right panel).

**Table 2.** Mass (M), momentum (P) and energy (E) obtained for the shocked and dense gas and corresponding velocity ranges used for the calculation.

| Molecule                   | M<br>( $M_{\odot}$ ) | P<br>( $M_{\odot} \text{ km s}^{-1}$ ) | E<br>(erg)                     | $\Delta V$<br>(km s <sup>-1</sup> ) |
|----------------------------|----------------------|--|--------------------------------|-------------------------------------|
| $\text{H}^{13}\text{CO}^+$ | $125 \pm 50$         | $(8 \pm 3) \times 10^2$                | $(4.5 \pm 1.8) \times 10^{40}$ | 6                                   |
| SiO                        | $100 \pm 60$         | $(2 \pm 1) \times 10^3$                | $(2.6 \pm 1.6) \times 10^{41}$ | 16                                  |

#### 4.2 SiO as probe of the shock interaction between IC443 and clump G: positive feedback driven by SNRs

The presence of such a large-scale shock interaction is further supported by the kinematic structure observed for the SiO emission and reported in Section 3.1. The SiO emission is indeed significantly blue-shifted with respect to the central velocity of the clump (Dickman et al. 1992) and it presents a global velocity gradient with the blue-shifted emission appearing toward the east-southeast and the red-shifted gas located toward the west-northwest. Such a kinematic structure cannot be reproduced by a collection of molecular outflows driven by low-mass protostars, which have been seen to be randomly oriented with respect to the parental clump, in star forming regions (Dunham et al. 2016; Stephens et al. 2017). On the contrary, the well-organised SiO kinematic structure is similar to that reported by

Cosentino et al. (2019) toward the molecular cloud G034 known to be interacting with the SNR W44 (Wootten 1977). Toward this region, the SiO emission is seen to be blue-shifted with respect to the central velocity of the cloud ( $42 \text{ km s}^{-1}$  Cosentino et al. 2019) and spatially associated with a  $4.5 \mu\text{m}$  extended ridge (Cosentino et al. 2018). The SiO emission toward G034 as seen with ALMA, shows a sharp gradient of  $2\text{-}3 \text{ km s}^{-1}$ , within  $3''$ , which is followed by a shallower gradient of  $5\text{-}6 \text{ km s}^{-1}$ , across  $>10''$  scales (equivalent to linear scales of  $0.15 \text{ pc}$ ). Our ARO and Yebes observations probe spatial scales of  $0.7\text{-}0.4 \text{ pc}$  and therefore cannot resolve with such detail the observed SiO emission. However, IC443 is  $1 \text{ kpc}$  closer than W44 ( $\sim 2.9 \text{ kpc}$ ) and its SiO emission is almost a factor of 2 more extended, which allows us to appreciate a clear shocked gas velocity gradient across the ridge. The highly blue-shifted SiO gas here observed is naturally explained when the geometry suggested by Troja et al. (2006) is considered. In this scenario, clump G is located in the foreground with respect to IC443 and hence the shock wave released by the SNR hits the clump from behind pushing and dragging the shocked gas toward the observer. The fact that the SiO blue-shifted emission appears directed toward the inner part of IC443, is likely due to the fact that the shock is impacting on the cloud with a certain angle with respect to the line of sight. This was first suggested by Dickman et al. (1992) and van Dishoeck et al. (1993) and is consistent with what was reported by Reach et al. (2019). These authors

modelled the interaction between IC443 and clump G as occurring through two CJ-type shocks of  $\sim 60 \text{ km s}^{-1}$  and  $\sim 37 \text{ km s}^{-1}$  and dynamical age  $5 \times 10^3$  and  $3 \times 10^3$  years, respectively and that are hitting the cloud with angles of  $\sim 60$ - $65^\circ$  with respect to the line of sight.

The multiple shocks driven by IC443 and impacting on clump G may be responsible for the  $\text{H}_2$  volume density profile reported in Figure 7. The higher densities seen at velocity  $\geq -5 \text{ km s}^{-1}$  may be associated with the initial stronger impact between the shocks and the cloud, from which the bulk of the SiO emission is likely arising. After this first compression, the gas is dragged and decelerates toward the observer, appearing as highly blue-shifted. This is also supported by the fact that the higher excitation of the shocked gas also occurs at velocity  $\geq -5 \text{ km s}^{-1}$  and decreases at more blue-shifted velocities.

From Figure 7, the  $\text{H}_2$  volume density of the shocked gas toward clump G is  $\geq 10^5 \text{ cm}^{-3}$  at all velocities, consistent with both the SiO(1-0) and (2-1) critical densities. These values are comparable to those required to ignite star formation in the ISM (e.g., [Parmentier 2011](#)).

Toward clump G, several studies have reported  $\text{H}_2$  volume densities of the pre-shocked gas in the range  $n(\text{H}_2) \sim 10^3$ - $10^4 \text{ cm}^{-3}$  ([van Dishoeck et al. 1993](#); [Dell'Ova et al. 2020](#)) i.e., slightly lower than those typically observed in dark clouds. This suggests that the shock propagation enhances the gas density by more than a factor of 10 and up to a factor of 100. By using XMM-Newton observations of clump G, [Troja et al. \(2006\)](#) identified a strong X-ray absorption and reported a  $n(\text{H})$  column density variation, along the line of sight, of  $5 \times 10^{21} \text{ cm}^{-2}$ . By considering such a variation and the post-shocked  $\text{H}_2$  gas density here measured, i.e.,  $10^5 \text{ cm}^{-3}$ , the length of the shocked region can be estimated as  $\sim 2.5 \times 10^{16} \text{ cm}$  (or 0.008 pc). When a shock velocity of  $25 \text{ km s}^{-1}$  is considered ([Dickman et al. 1992](#)), the time since the first shock interaction is therefore of  $\sim 300$  years. For such a time-scale, a factor of 10 density enhancement in the post-shocked gas can be explained as due to both the shock propagation, the presence of radiative cooling processes and significant energy dissipation by particles acceleration. The presence of such mechanisms is indicated by the detection of non-thermal X-ray emission, toward clump G (e.g., [Bocchino & Bykov 2000](#)). A factor of 100 is instead well beyond the typical density enhancements caused by shock propagation. We therefore suggest that the pre-shocked gas density toward clump G is at least of  $n(\text{H}_2) \sim 10^4 \text{ cm}^{-3}$ . This supports the idea that clump G may have been a coherent dense structure pre-existent to the SNe event.

Finally, we note that the high-density measured in the post-shocked gas may help to explain the enhanced  $\gamma$ -ray emission measured toward clump G ([Albert et al. 2007](#); [Acciari et al. 2009](#); [Abdo et al. 2010](#)).

#### 4.3 The $\text{H}^{13}\text{CO}^+(1-0)$ emission toward clump G: shock chemistry product or molecular cloud in the making?

Emission from  $\text{H}^{13}\text{CO}^+$  is a good probe of the dense gas distribution in molecular clouds (e.g., [Vasyunina et al. 2011](#)). As shown in Figure 2, the  $\text{H}^{13}\text{CO}^+$  emission is spatially coincident with the shocked gas emission but less extended. No significant  $\text{H}^{13}\text{CO}^+$  emission is detected outside the shocked region, supporting the low-density values measured for the ambient gas ([van Dishoeck et al. 1993](#)). In addition, the  $\text{H}^{13}\text{CO}^+$  spectrum reported in Figure 4 shows a profile similar to that of both the SiO(1-0) and (2-1) transitions. The spatial and spectral similarities between the SiO and  $\text{H}^{13}\text{CO}^+$  emission hint toward a common nature of the two species. In this scenario, the  $\text{H}^{13}\text{CO}^+$  emission is likely a consequence of the ongoing shock chemistry. Indeed, emission from ions such as  $\text{HCO}^+$  is known to be

enhanced either in the earliest stages of the shock (see Figure 5 in [Flower & Pineau des Forêts 2003](#)) or in the far post-shock gas, when the temperatures have gone down to  $\sim 30 \text{ K}$  ([Bergin et al. 1996](#)). This scenario is consistent with the idea that the cloud was pre-existent with respect to the SNR, as already suggested by [Dickman et al. \(1992\)](#), more recently discussed by [Ustamujic et al. \(2021\)](#) and as discussed in Section 4.2. This is also supported by the fact that the dense and shocked gas mass estimates are similar and that the emission is spatially localised with respect to the  $4.5 \mu\text{m}$  ridge, direct probe of the shock front.

Alternatively to this scenario, the  $\text{H}^{13}\text{CO}^+$  emission may be probing the material of clump G that is being shock-compressed with a process similar to that described by [Inutsuka et al. \(2015\)](#). Here, bubbles due to stellar feedback expand into the clumpy multi-phase ISM, driving multiple episodes of shock compression into the nearby low-density material participating in the assembling of dark clouds. In the IC443 scenario, pre-existent low-density material of clump G may have been compressed by the propagating shocks to densities sufficient to enable the collisional excitation of the  $\text{H}^{13}\text{CO}^+(1-0)$ . This may be supported by the fact that the dense gas mass reported in Table 2 is comparable to the mass of the ambient gas measured from multiple CO transitions by [Dell'Ova et al. \(2020\)](#). However, we note that the peak velocity of the  $\text{H}^{13}\text{CO}^+$  emission ( $\sim 8 \text{ km s}^{-1}$ ) does not coincide with that of the ambient cloud in [Dell'Ova et al. \(2020\) \( \$\sim 3.5 \text{ km s}^{-1}\$ \). We therefore suggest that the  \$\text{H}^{13}\text{CO}^+\$  emission is mainly due to the ongoing shock chemistry in IC443. We note that the dense gas mass here estimated from  \$\text{H}^{13}\text{CO}^+\$  is a factor of 2-3 higher than that reported by \[Dickman et al. \\(1992\\)\]\(#\) for clump G, i.e.,  \$\sim 40 \text{ M}\_\odot\$ , obtained from  \$\text{HCO}^+\$  emission. However, these authors did not take into account possible optical depth effects in the  \$\text{HCO}^+\$  emission.](#)

#### 4.4 Negative feedback driven by IC443: comparing observations with model predictions.

In Section 3.3, we have investigated the mass, energy and momentum calculated for both the dense and shocked gas detected toward clump G. As reported in Table 2, we estimate a mass of the shocked gas of  $\sim 100 \pm 60 \text{ M}_\odot$ . Considering the length of the shocked region reported in Section 4.2, i.e.,  $2.5 \times 10^{16} \text{ cm}$  or 0.008 pc, the volume of the shocked region is  $1.8 \times 1.6 \times 0.008 \text{ pc}^3$ . For the measured post-shocked gas density of  $n(\text{H}_2) \sim 10^5 \text{ cm}^{-3}$ , the mass enclosed in such a volume is  $\sim 90 \text{ M}_\odot$ . This provides an independent confirmation to the values here reported.

IC443 is known to be interacting with the molecular material toward three additional sites, named clumps A, B, C ([Dickman et al. 1992](#)). Assuming that the momentum transferred into clumps A, B and C is equal to that measured toward clump G, we estimate a momentum transferred from the SNR into the surrounding molecular material in the range  $\sim 3.2$ - $8 \times 10^3 \text{ M}_\odot \text{ km s}^{-1}$ . Since the strongest interaction is known to be occurring toward clump G ([Claussen et al. 1997](#)), such a value should be regarded as an upper limit.

State-of-the-art numerical simulations predict the amount of momentum transferred from an expanding SNR into the nearby ISM to be  $(1.5) \times 10^5 \text{ M}_\odot \text{ km s}^{-1}$ , when a kinetic energy of  $10^{51} \text{ ergs}$  released by the SNR is assumed ([Kim & Ostriker 2015](#); [Li et al. 2015](#); [Marrizzi et al. 2015](#); [Iffrig & Hennebelle 2015](#); [Zhang & Chevalier 2019](#)). Assuming such kinetic energy for IC443 ([Ustamujic et al. 2021](#)), we estimate that the momentum carried away by the interaction between the SNR shocks and the surrounding molecular material represents  $< 10\%$  of the total imprinted momentum.

More in general, considering the momentum of the shocked and

dense gas reported in Table 2,  $2 \times 10^3 \text{ M}_\odot \text{ km s}^{-1}$ , and the SiO and  $\text{H}^{13}\text{CO}^+$  emission spatial coverage of  $1.8 \times 1.6 \text{ pc}^2$  and  $1.3 \times 1.2 \text{ pc}^2$  respectively, we estimate the *momentum per unit area* of the gas to be  $\sim 500\text{--}690 \text{ M}_\odot \text{ km s}^{-1} \text{ pc}^2$ . For this estimate, we assume the gas emission to be plane parallel and along the line of sight. We note that the momentum per unit area here estimated should also be regarded as an upper limit, since the interaction toward other sites is likely to be weaker than that observed toward clump G. Considering for the SNR a diameter of  $45''$  (Green 2019), we estimate the area of the bubble to be  $\sim 1800 \text{ pc}^2$ . Since the molecular material surrounding IC443 is distributed as a toroid around the expanding bubble (Troja et al. 2006), we assume that the SNR effective area that is directly in contact with molecular material is  $\sim 20\%$  and in any case  $< 50\%$ , since IC443 is expanding into an atomic cloud in the North. Therefore, we estimate the momentum carried by the molecular material to be  $\sim 1.8\text{--}2.5 \times 10^5 \text{ M}_\odot \text{ km s}^{-1}$ . This is 35–50% the momentum typically injected by a SNR.

Our calculation indicates that the molecular material can be a relevant carrier of the momentum injected by SNR feedback into the ISM. The importance of this resides in the fact that the cold dense molecular material of the ISM is the primary fuel of star formation in galaxies. The imprinted momentum contributes to maintain the level of turbulence in the ISM (Padoan et al. 2016), a key ingredient in the star formation process. Finally, we note that the momentum deposited by SNRs into the ISM is further increased by the presence of accelerated cosmic rays. Since their energy is not radiated away during the Sedov-Taylor phase, cosmic ray further support the SNR expansion and prolong the momentum deposition phase. As a result, the momentum injected by SNRs into the nearby material can be boosted by a factor of 5–10, for density of the ISM  $> 10^2 \text{ cm}^{-3}$ . For a more detailed discussion we refer to Diesing & Caprioli (2018).

## 5 CONCLUSIONS

In this paper, we have used SiO(2-1) and  $\text{H}^{13}\text{CO}^+$ (1-0) observations obtained as part of SHREC as well as complementary SiO(1-0) observations obtained by 40m antenna at the Yebes Observatory to investigate the negative and positive feedback driven by the SNR IC443 onto the molecular clump G. Our results can be summarised as follows:

i) The SiO emission shows an elongated morphology, spatially coincident and parallel to an extended ridge of shocked gas seen at  $4.5 \mu\text{m}$ . The SiO kinematics is organised as a well-ordered structure, with the shocked material being systematically blue shifted with respect to the central velocity of the SNR.

ii) The shocked gas kinematic structure as well as its inferred mass ( $100 \text{ M}_\odot$ ), momentum ( $2 \times 10^3 \text{ M}_\odot \text{ km s}^{-1}$ ) and energy ( $2.6 \times 10^{41}$  ergs) cannot be solely explained as the product of ongoing star formation activity in clump G. Therefore we conclude that the bulk of the SiO emission arises from the ongoing shock interaction between the clump and IC443.

iii) Toward clump G, the shock propagation enhances the gas density to values  $n(\text{H}_2) \geq 10^5 \text{ cm}^{-3}$ , a factor  $> 10$  higher than the density of the pre-shocked material and consistent with the densities required to ignite star formation in molecular clouds.

iv) The dense gas mass estimated from the  $\text{H}^{13}\text{CO}^+$  emission is similar to that estimated for the shocked gas. Furthermore, the dense gas emission is spatially concentrated toward the  $4.5 \mu\text{m}$  ridge. We

interpret this result as evidence that the  $\text{H}^{13}\text{CO}^+$  emission is likely due to shock chemistry effects and that clump G was pre-existent with respect to IC443.

v) Finally, we estimate that between 35–50% of the momentum injected by IC443 is transferred to the molecular phase of the ISM, making the molecular material an important momentum carrier in sites of SNR-cloud interactions. The injected momentum helps maintain turbulence in the molecular ISM that fuels star formation in galaxies.

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## DATA AVAILABILITY

The SiO and  $\text{H}^{13}\text{CO}^+$  data cubes used for the study here presented will be distributed upon request to the corresponding author. Data obtained as part of SHREC will also be made publicly available through dedicated website in the coming months.

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