EXTRAGALACTIC CHEMISTRY OF STARBURSTS: THE FIRST VIEW

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Abstract

In this paper we briefly review some of the key problems in the study of the extragalactic chemistry of nuclear starbursts. We will discuss the relevance of large-scale shocks in the processing of the ISM during a massive star formation episode. We present the results from a high-resolution survey searching for emission of the SiO molecule among a sample of prototypical starbursts, including NGC 253, M 82 and IC 342. We end by emphasizing what would be the future contributions of HIFI to the study of the chemistry of molecular gas in the nuclei of starbursts.

Key words: Galaxies: chemistry – Galaxies: dynamics – Missions: FIRST

1. Introduction

Results from mm and FIR ISO surveys underline that the general properties of ISM in starburst (SB) galaxies differ significantly from quiescent star-forming disks or AGNs. Although the detection of rotational transitions of high dipole molecules reveals the existence of large amounts of dense ($n(H_2)>10^5$) and hot (T$\sim$30-50K) gas in SBs, accurate estimates of the mass of gas directly forming stars are difficult to obtain. Molecular gas in SBs has a complex *multi-phase* nature, as confirmed by recent studies made in nearby galaxies (see for example the case of M 82 discussed by Mao et al. 2000). To probe the gas directly associated with massive star formation requires the observation of high-J rotational transitions of molecules, many of which being not observable from ground-based telescopes. There is neither a clear picture of the physical/chemical status of the gas and how these evolve as the nuclear SB proceeds. The relative weight that can be attributed to shocks and to radiation fields as the driving engines of the evolution of molecular gas in these galaxies is still a matter of debate. To settle the question, specific tracers of shocked regions and Photon Dominated Regions(PDR) must be used.

Any plausible scenario modelling the evolution of a SB episode contemplates the occurrence of large-scale shocks at different stages. During the onset of the starburst (hereafter phase **I**), density wave instabilities induce gravitational torques and drive the infall of large amounts of gas towards the nucleus. Large-scale shocks may be at work related to an enhanced compression of gas and an increased rate of cloud-cloud collisions in the potential wells of spiral arms and/or bars. Once the first massive stars are formed in a second phase (**II**), bipolar outflows give rise to shocks in molecular gas. Finally, with the appearance of the first superonovae (SN) explosions (phase **III**) , the gas gets heated and shocked during the expansion of the so-called *hot bubble*.

To explore the influence of large-scale shocks and/or massive star formation in the chemistry of molecular gas, we have undertaken a survey of SiO in a sample of nearby SBs. The choice of SiO is justified as this molecular species is a privileged tracer of shock chemistry. Galactic studies show that the sputtering of dust grains enhances the absolute abundance of SiO in young stellar objects (YSO) where $X_{SiO}\sim10^{-7}$-$^{-8}$ (Nisini et al. 2000) and, also, close to SN remnants (SNR), where $X_{SiO}\sim10^{-9}$ (Cesarsky et al. 1999; van Dishoeck et al. 1993). In contrast, SiO is depleted in quiescent dark clouds ($X_{SiO}\sim10^{-12}$) and, to a lower extent, in PDRs (where $X_{SiO}\sim10^{-11}$-$^{-10}$).

A precedent survey in the center of our Galaxy has discovered widespread thermal SiO emission from a 500 pc circumnuclear disk (CND), which is not related to a starburst event (the Galaxy center hosts no recent starburst); this CND is however linked with large-scale shocks (Martín-Pintado et al. 1997). Surprisingly, the link between SiO emission and massive star formation does not apply in the center of our Galaxy. This result has motivated our search for SiO emission in the nuclei of nearby starbursts.

2. The SiO extragalactic survey

We have looked for emission in the (v=0) J=2–1, 3–2 and 5–4 rotational transitions of SiO among a sample of 10 nearby galaxies, including the prototypical starbursts NGC 253, M 82 and IC 342. We also observed simultaneously the J=1–0 line of $H^{13}CO^+$. The ratio of integrated intensities R=I(SiO(2–1))/I($H^{13}CO^+$(1–0)) will be used to estimate X_{SiO} (note that n_{crit} are alike for the two lines). On the other hand the SiO line ratios help to estimate the physical parameters of the clouds. The first part of this survey has been performed with the IRAM 30m telescope.

The 30m results already indicate that thermal emission of SiO is widespread, forming r$\sim$300 pc CNDs in

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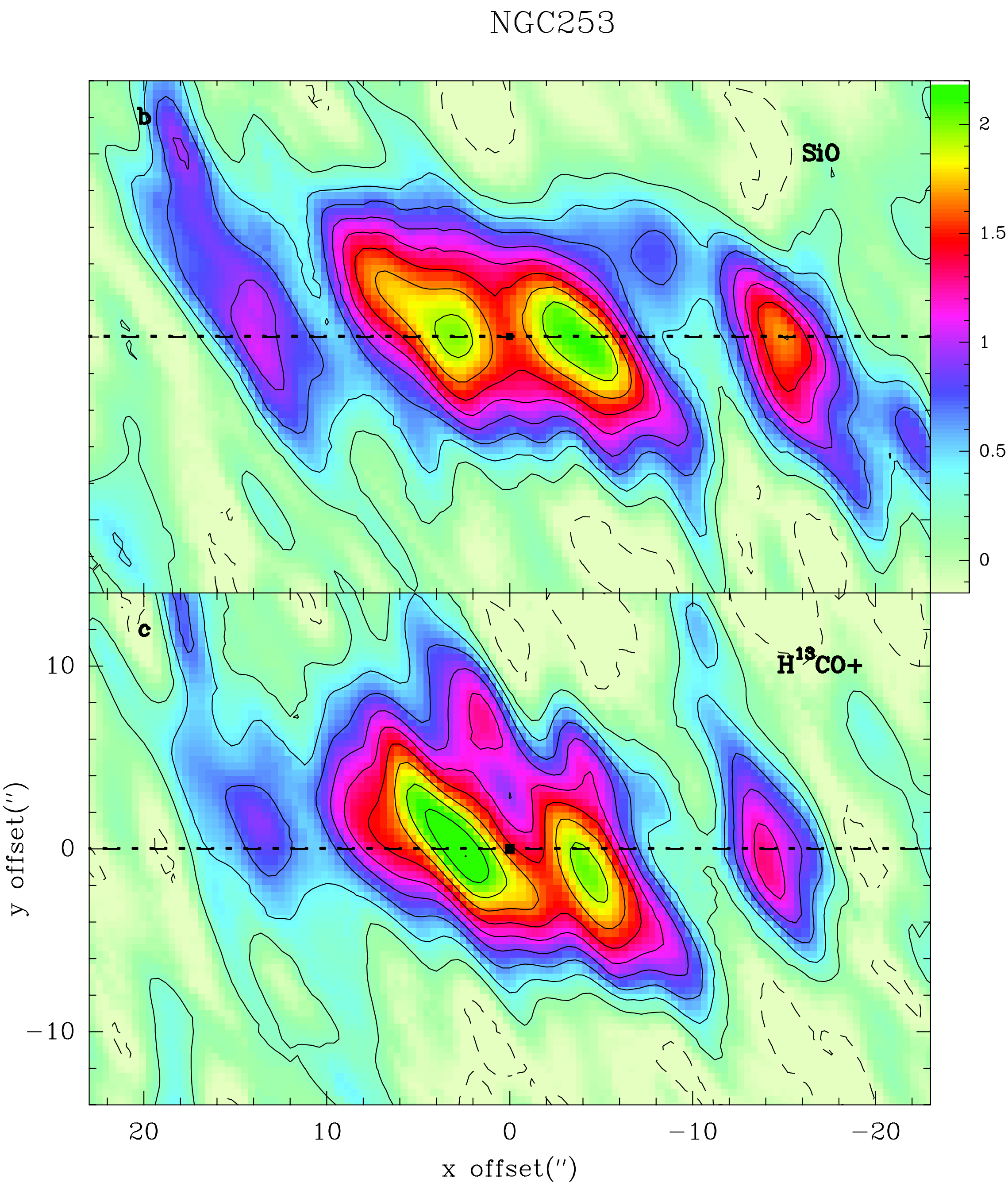

Figure 1. **(a,top)**: *SiO(v=0,J=2–1) integrated intensity contours towards the center of NGC 253. x and y offsets (in arcsec with respect to the dynamical center) are parallel to the major and minor axes of the stellar bar. Contours are -0.2, 0.2 to 2.2Jy.kms^{-1}beam^{-1} by steps of 0.25Jy.kms^{-1}beam^{-1}. Orientation as in Figure 1a.* **(b,bottom)**: *same as (b) but for the J=1–0 line of $H^{13}CO^{+}$.*

NGC 253 and IC 342. It is however very weak in M 82. $<X_{SiO}>$ abundance is highly variable within the sample: it can reach ~10^{-9} in NGC 253 and IC 342, and 1/50 of this value in M 82. The physical parameters of SiO clouds are also markedly different: SiO clouds are dense (n(H_2)~10^{5-6}cm^{-3}) and hot (T_{kin} ~50-75K) in NGC 253, but relatively diffuse (n(H_2)~10^4cm^{-3}) and cold (T_{kin} ~20-40K) in IC 342.

For some of the galaxies in the sample we have obtained high-resolution images in the SiO(2–1) and $H^{13}CO^{+}$(1–0) lines, using the IRAM Plateau de Bure interferometer. Results from the high-resolution SiO maps made in NGC 253 and M 82, the first SiO images of external galaxies, are presented below.

3. The interferometer SiO maps

Figures 1a-b show the SiO/$H^{13}CO^+$ maps of NGC 253 discussed by García-Burillo et al. 2000. Emission from the two species is extended in the nucleus of NGC 253. The bulk of the SiO emission arises from a (600pc×250pc) circumnuclear disk (CND) with a double ringed structure. The inner ring, of radius r∼60pc(4″), viewed edge-on along PA=51°, hosts the nuclear starburst; the outer pseudo-ring opens out as a spiral-like arc up to r∼300pc (20″). The kinematics of the gaseous disk, characterized by strong non-circular motions, is interpreted in terms of the resonant response of the gas to the barred potential. The inner ring (which hosts the nuclear starburst) would correspond to the inner Inner Lindblad Resonance(iILR) , whereas the outer region is linked to the onset of a trailing spiral wave across the outer ILR(oILR).

The SiO shows a high average fractional abundance in the CND of $<X(SiO)>\sim 1.5\times 10^{-10}$. This is more than an order of magnitude above the predicted value of a PDR, and shocks are needed to explain it. Moreover, X(SiO) varies by at least an order of magnitude between the inner starburst region, which dominates the global emission, where we derive $X(SiO)\sim 1\text{–}2\times 10^{-10}$, and the outer region, where X(SiO) reaches a few 10^{-9}. Large-scale shocks induced by the crowding of clouds orbits across the oILR in the outer region seem to be more efficient than massive star formation at rising the abundance of Silicon. Similarly, the emission of SiO is detected well beyond the nuclear starburst of IC 342. The 30m map of this galaxy shows that there is a link between the occurrence of shocks along the bar-driven spiral and an enhancement of X(SiO). This confirms that the relation between SiO abundance and massive star formation is not straightforward.

Compared to NGC 253, the SiO map of M 82 shows a completely different picture: emission from the SiO line hardly comes out of the noise and the derived absolute abundance of SiO is 1–2 orders of magnitude lower than in NGC 253 (see Figure 2). Although the nuclear starbursts of NGC 253 and M 82 are in many respects similar (Thornley et al. 2000), they show remarkable differences in their SiO emission.

There are several sources of shock chemistry along the SB sequence that may explain the highly variable abundance of SiO among the galaxies in our sample:

- Large-scale shocks driven by density waves (spirals, bars) acting during phase **I** can account for the outer SiO disks in IC 342 and NGC 253, which both seem to extend beyond the nuclear SB.
- Outflows driven by YSOs during phase **II** can explain the measured average abundances of SiO in the inner disks of NGC 253 and IC 342.
- During phase **III**, shocks driven by SN explosions, probably less efficient than bipolar outflows, could explain the abundance of SiO in the inner disk of the Galaxy. Interaction of the winds from Wolf-Rayet Stars with neutral gas have also been suggested as a potential mechanism.
- In contrast, the low value of X_{SiO} measured in the M 82 SB can be reproduced by standard PDR models, with no need of processing by large-scale shocks.

An estimate of the average X_{SiO} could help to locate a starburst galaxy along the described evolutionary track. The interpretation of X_{SiO} in terms of aging effects in SBs requires to consider the efficient re-condensation of SiO onto the dust grains (with a time scale as short as T_{scale} $\sim 10^{3-4}$yrs). Modelling mid-infrared ISO data, Thornley et al. (2000) concluded that SB episodes are short-lived ($\sim 10^{6-7}$ yrs). However, there is evidence that bursts of star formation in galaxies are recurrent. This implies that SiO gives an *instantaneous* picture of the status of large-scale shocks in SBs.

There remains however a wealth amount of unknowns, concerning the accurate determination of the mass of gas involved in these shocks, the physical parameters and the chemical abundances of the shocked gas and how this fits within the different scenarios modelling the evolution of a nuclear SB. The next section briefly summarizes what could be the potential contributions of HIFI to this field of research. The FIRST satellite will have an unprecedented sensitivity which surpasses by large the capabilities of other infrared facilities, such as ISO (roughly by a factor ∼30). This will allow the detection of new species and the observations of line transitions which were not accessible so far, especially different lines of H_2O. Most noticeably, the high velocity-resolution of the HIFI instrument will be essential to study the kinematics of molecular gas and possibly establish a link between peculiar velocities (non-circular motions) and the chemical processing of the gas by shocks.

4. Extragalactic chemistry with HIFI

A complete characterization of the molecular gas in SBs requires the observation of a large number of species. The HIFI heterodyne instrument on board the FIRST satellite will allow to complete this inventory, developing different observational programs:

- **I. Observation of tracers of gas directly associated with massive star formation**: These will help to constrain the physical parameters of SF clouds ($n(H_2)$, T_{kin}), the mass of gas forming stars and the SF efficiency. The HIFI instrument may observe, among other species:
  - Mid/high–J sub-millimeter rotational transitions of CO.
  - Mid/high–J sub-millimeter rotational transitions of high-dipole moment
    molecules such as CS, HCN, HCO^+ and CN.

  Typically, several rotational transitions of molecules with absolute abundances $X>10^{-8}$ can be detected

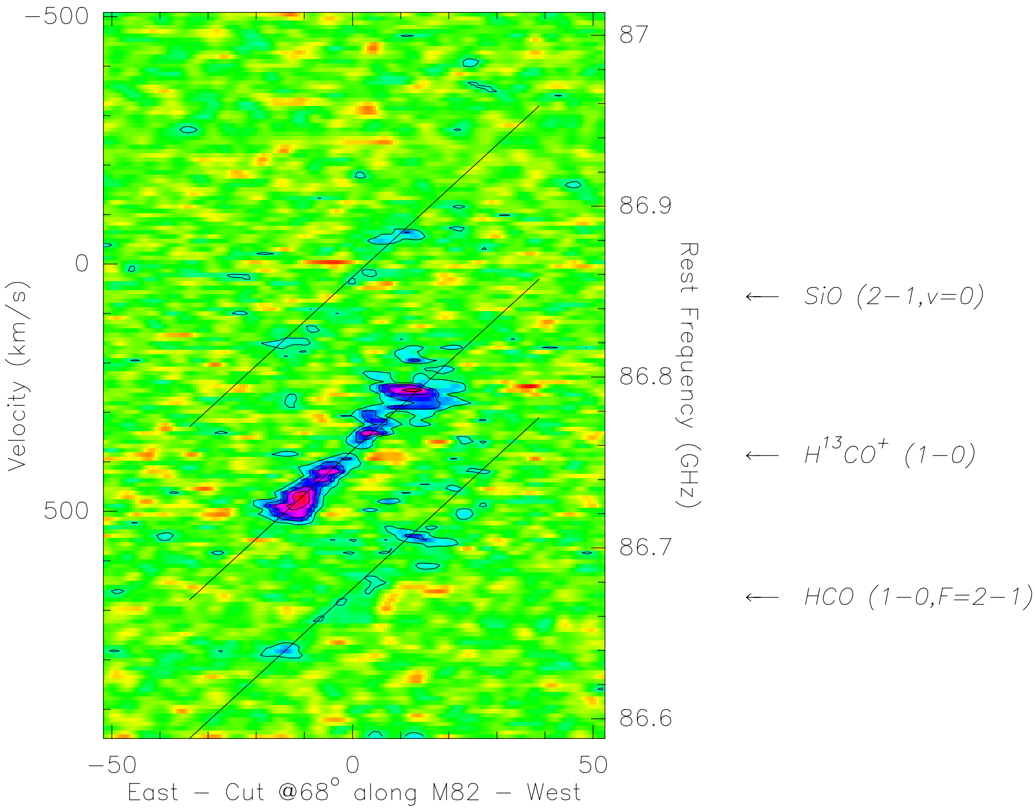

Figure 2. The major axis position-velocity diagrams taken at the center of M 82 in the SiO(v=0,J=2-1) $H^{13}CO^{+}$(1–0) and HCO(1–0) lines. x offsets are along major axis and referred to the dynamical center. v scale arbitrary (refer instead to freq scale). Contours are 20% to 100% by steps of 20% of the maximum value 0.012Jybeam^{-1}.

with sufficient signal to noise ratio (S/N>5), integration times of ∼1 hour and a frequency resolving power R>10^4 for a prototypical SB located within a distance D=50Mpc.

– **II. Observation of privileged tracers of shock chemistry**:
  Although our SiO study already indicates that shock chemistry is at play in SBs, the FIRST satellite will allow to probe a number unexplored tracers of shock chemistry:

  – The low excitation H_2O lines will be detected with FIRST in a large sample of SBs.
  – Mid/high–J rotational transitions of SiO, SO and CH_3OH could be detected in the most intense SBs and used as tracers of dense shocks.
  – Rotational lines of light hydrides could be used as tracers of diffuse shocks, testing the transformation of HI gas into H_2.
  – Finally, models of shock excitation for the mid/high–J rotational transitions of CO could be confronted to PDR models.

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