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CS in nearby galaxies: distribution, kinematics and multilevel studies

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Recently, several high resolution studies of extragalactic CO and even of its rare isotopic substitutions have been published making use of advanced mm-wave interferometers and single-dish telescopes. From these studies, the morphology and kinematics of the molecular gas can be derived and compared to the distribution of stars and dust. On the other hand, the recent detection of many complex extragalactic molecules (see Henkel et al. 1987, 1988 and references therein) opens up the possibility to derive from observations of many transitions of the same molecule further important parameters, like kinetic temperature, gas density and excitation conditions. These are difficult to derive from CO alone, because of the low degree of excitation required to thermalize CO and because of severe beam dilution expected in these distant sources. While NH₃ is a good thermometer for extragalactic sources (Martin and Ho 1987), CS, which has been previously detected by Henkel and Bally (1985) toward the galaxies IC 342 and M 82, is a relatively abundant molecule, which is suitable as a probe to estimate H₂ densities (e.g. Linke and Goldsmith 1980).

As a result of observations at the IRAM 30-m telescope, maps of the distribution of the J=2-1 transition of CS toward the galaxies IC 342 and NGC 253 are presented. The distribution of the CS emission from NGC 253 is consistent with that of the CO 1-0 line. The distribution of the CS emission from IC 342, however, resembles more that seen in the CO 3-2 line. For the first time, the detection of the isotopic substitution C³⁴S is reported toward an external galaxy: The C³⁴S 2-1 line has been detected toward NGC 253 and M 82 and the C³⁴S 3-2 line has been detected tentatively toward M 82. Also for the first time, extragalactic CS has been observed in the 3-2 (toward NGC 253, IC 342 and M 82) and 5-4 (NGC 253 and IC 342) transitions.

The results obtained from the observations of several transitions and isotopic substitutions of CS can be compared with model computations using a non-LTE statistical equilibrium program. Since CS requires densities an order of magnitude higher than CO to be excited, it may seen in a smaller volume than CO. Even in the optically thick case, the observed T_{MB} may be much smaller than the excitation temperature T_{ex} and, because of our lack of information on the beam-filling factor, only the ratios of different lines enter in our multi-level study. For this, we had to make some assumptions on geometry, since our beam size differs from transition to transition and time did not permit to map the CS 3-2 and 5-4 emission.

The values of $T_{MB}(\text{CO})$ measured toward IC 342, NGC 253 and M 82, 10K, 9 K and 15 K (Lo et al. 1984, Canzian et al. 1988, Lo et al. 1987), can only be considered as lower limits to T_{kin} . However, these relatively high values show that the beam filling factor of CO within a 7" beam is probably $\geq 10\%$. From observations of lines from the CS and C³⁴S isotopes, one can directly estimate the optical depth of the CS lines without having to account for the unknown beam filling factor. For this, we assumed optically thin C³⁴S emission and a relative ³²S/³⁴S abundance of 23 (Wannier 1980).

For our multilevel analysis, we computed the expected intensities of the C³⁴S 2-1 line as well as of the CS 3-2 and 5-4 lines relative to the CS 2-1 transition. In order to determine the physical parameters, we first obtained for each source the ratio of the integrated intensities in the 2-1 transition of CS and C³⁴S, which could be measured with the same angular resolution. The such determined ratios are $9(\pm 2)$ for NGC 253 at the (0",0") offset, > 4.5 for IC 342 at (-10",0") and $16(\pm 5)$ for M 82 at (-10",0"). Additionally, we determined line intensity ratios for transitions of the CS main isotope.

NGC 253 The H₂ density and the column density derived from the intensity ratio of the 2-1 transitions of CS and C³⁴S determined above and of the ratio of the line intensities of the 2-1 and 5-4 transition are, assuming $T_{kin}=60$ K, $n(\text{H}_2) = 10^{4.6} \text{cm}^{-3}$ and $N(\text{CS}) = 2(\pm 1) 10^{14} \text{cm}^{-2} \Delta v_{1/2}$. With $\Delta v_{1/2}=160$ km s⁻¹, $N(\text{CS}) = 3(\pm 1) 10^{16} \text{cm}^{-2}$. Here, $N(\text{CS})$ is the column density averaged over the CS emitting

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region. All column densities are 'in the line of sight' and not reduced to 'face-on'. From a comparison of the line temperature expected from our model and the actually observed value reduced to an 11" region, the 2—1 emitting gas has a clumping factor of ~ 0.17 . From this, the column density averaged over an 11" region is $0.5 \cdot 10^{16} \text{cm}^{-2}$.

If we take the ratio from the 3—2 and 5—4 transitions, for which assumptions on geometry are not so important because of the more similar beam width, the density even becomes $n(\text{H}_2) = 10^{5.4} \text{cm}^{-3}$ for $T_{\text{kin}}=60 \text{K}$ and $10^{5.2} \text{cm}^{-3}$ for $T_{\text{kin}}=90 \text{K}$. These different H_2 densities derived from the various line ratios could be explained if the bulk of the CS gas is lower density gas (seen in the 2—1 transition) containing higher density condensations (traced out by the 5—4 line).

Canzian et al. (1988) derive for the NGC 253 bar an average H_2 column density of $1.5 \cdot 10^{23} \text{cm}^{-2}$. From this value, the relative CS abundance is $X(\text{CS})=3 \cdot 10^{-8}$.

IC 342 For IC 342, we have only a very crude upper limit on the optical depth, since we did not detect emission from C^{34}S . From observations of the 2—1, 3—2 and 5—4 lines, the maximum density compatible with our observations is, in the optically thin limit, $n(\text{H}_2) = 10^{5.0} \text{cm}^{-3}$. If the CS is optically thick, densities can become lower. These values are consistent with the upper limit derived from CH_3OH by Henkel et al. (1987). Using our model, we have calculated the column density of CS averaged over an 11" region in the optically thin case, which is required to reproduce the observed value of T_{MB} . For $n(\text{H}_2) \sim 5 \cdot 10^4 \text{cm}^{-3}$, we require $N(\text{CS}) = 1.5(\pm 0.5) \cdot 10^{14} \text{cm}^{-2}$. Combining this value with the H_2 column density of $\sim 7 \cdot 10^{22} \text{cm}^{-2}$ derived from CO multi-isotope studies (Eckart et al. 1989), the relative CS abundance toward the center of IC 342 is $X(\text{CS}) \sim 2 \cdot 10^{-9}$.

M 82 From the ratios of the CO 2—1 and 1—0 lines, the kinetic temperature of the molecular gas near the nucleus of M 82 is probably $\sim 50\text{K}$ (Knapp et al 1980, Sutton et al. 1983). For M 82, the intensity of the C^{34}S emission at the $(-10'', 0'')$ offset shows that the CS lines are only moderately saturated. If we assume that this is also the case for the $(0'', 0'')$ position were the 3—2 line of CS was observed, from the 3—2 and 2—1 line intensities, the H_2 density of the CS emitting gas at $(0'', 0'')$ is $< 10^4 \text{cm}^{-3}$. From the ratio of the integrated intensity of the 2—1 and 3—2 transitions of C^{34}S , $n(\text{H}_2) \sim 10^4 \text{cm}^{-3}$ at the peak $(-10'', 0'')$. However, the highest density compatible with the error limits of our C^{34}S observations is 10^5cm^{-3} . H_2CO data indicate, however, that even higher densities may exist in this region, which could be confirmed by observations of the CS 5—4 line.

Toward the nucleus of M 82, Lo et al. (1987) find a mean H_2 column density of $2.6 \cdot 10^{22} \text{cm}^{-2}$. Assuming similar excitation conditions for the CS as in the case of IC 342, the CS column density is $\sim 7(\pm 3) \cdot 10^{14} \text{cm}^{-2}$ and the relative abundance of CS is $X(\text{CS}) = 1.5(\pm 1) \cdot 10^{-9}$.

Accounting for the uncertainties in the determination of the H_2 column densities, the values observed for all galaxies are compatible with those found in Galactic molecular clouds where relative CS abundances of $10^{-7.8} \dots 10^{-9.0}$ have been measured.

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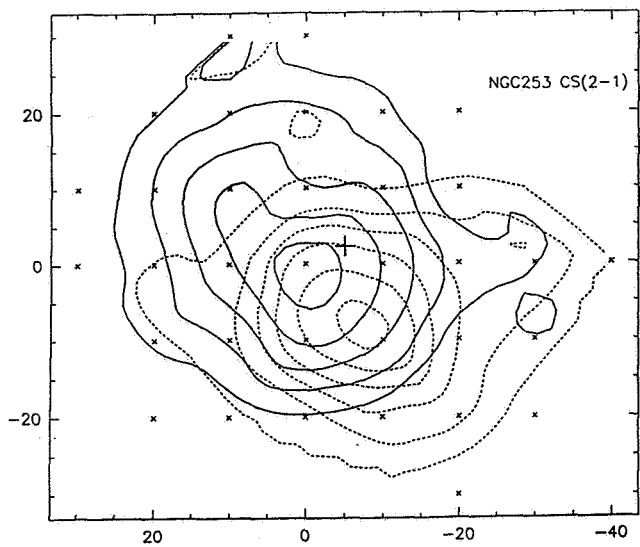


Figure 1. The distribution of the integrated CS 2—1 emission toward NGC 253. The reference position is $\alpha(1950) = 0^h45^m06.0^s$, $\delta(1950) = -25^\circ33'36''$. The solid contours are integrated from 50 to 250 km/s, the dashed contours from 250 to 450 km/s.

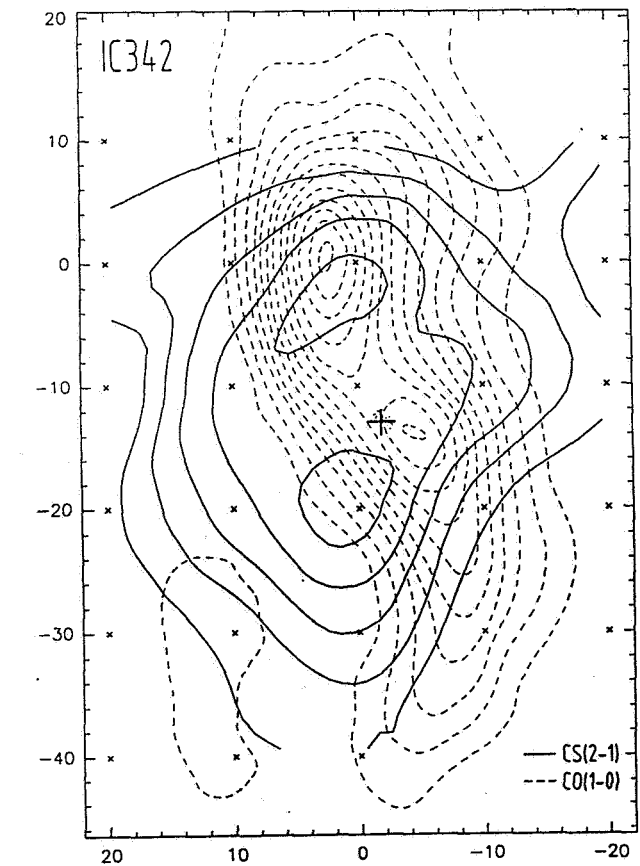


Figure 3. The integrated CS 2—1 emission toward IC 342 (reference position $\alpha(1950) = 3^h41^m57.5^s$, $\delta(1950) = 67^\circ56'40''$). The overlay shows the integrated CO 1—0 emission (Lo et al. 1984).

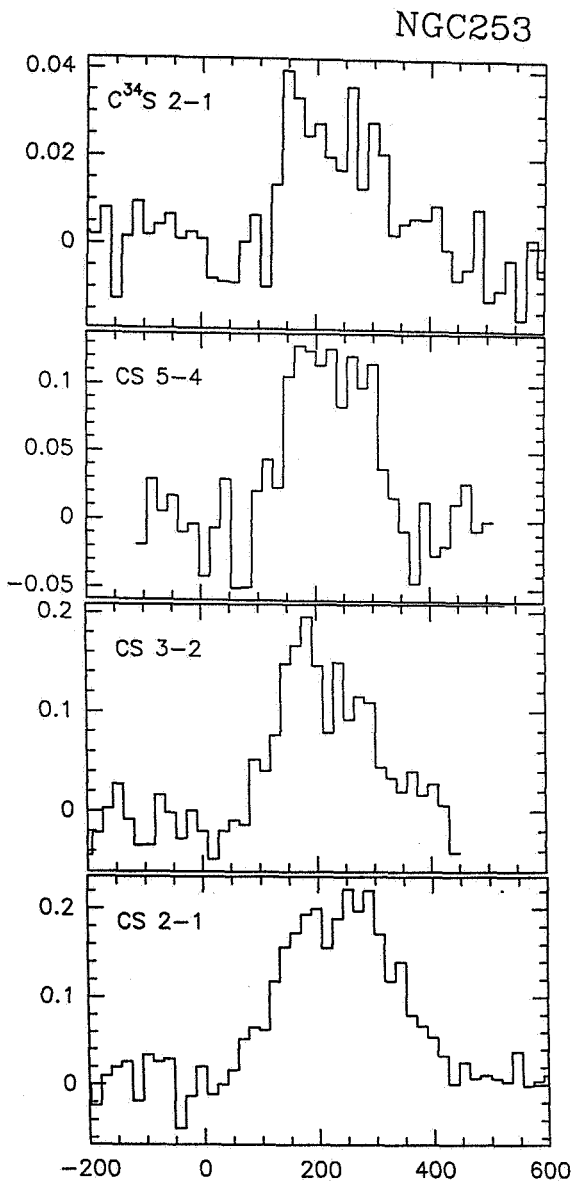


Figure 2. A compilation of the CS transitions measured toward NGC 253.