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On the frequency of the CS (J:2→1) and (J:5→4) transitions ⋆

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Abstract. While conducting high signal-to-noise ratio (SNR) observations of multiple transitions and different isotopomers of CS, SO and CO towards L183 (also known as L134N), we found that the CS (J:2→1) line frequency established by Kuiper et al. (1996) during observations towards L1498 was in disagreement with our observations. We have consequently repeated their observations towards that object, but in a slightly different manner by observing simultaneously the CS (J:2→1) line at 98 GHz and the CCS (J_N:$8_7 \rightarrow 7_6$) line at 94 GHz with the same telescope and the same receivers therefore eliminating the possibility of errors associated with either software or hardware. We found that our L183 data was best described with the standard frequency of 97980.95 MHz. We also found a real difference in the velocity position of the CS and CCS peaks in L1498, but one only half that reported by Kuiper et al. (1996). Most importantly, we have established that the L1498 cloud is not well-suited for setting the CS (J:2→1) frequency despite the exceptional narrowness of the lines. The CS (J:2→1) line shape is far from Gaussian and suffers from strong effects, due either to large scale movements (infall and/or rotation), or to self-absorption, or both. These results and other works (Lemme et al. 1995, Lee et al. 1999) have convinced us that these observations are consistent with the standard CS (J:2→1) line frequency. We also checked the $C^{34}S$ (J:2→1) and the CS (J:5→4) transitions and found a major discrepancy for the latter with the JPL catalogue. Finally, CS transitions have been recently re-measured in the laboratory by Gottlieb et al. (2001) with high precision and are found to be consistent with our interpretation.

Key words. Radio lines : ISM – ISM : molecules – ISM : individual objects : L183 – ISM : individual objects : L1498

1. Introduction

Several authors in the past (Snell et al. 1982, Kuiper et al. 1996, hereafter KLV and Lee et al. 1999) have had trouble interpreting astronomical data of the low rotational transitions of CS and $C^{34}S$ owing to small discrepancies in the rest frequencies measured by individual laboratories. These inconsistencies have led astronomers to establish the rest frequencies of certain transitions by interpretation of their astrophysical results towards cold sources where the lines are sufficiently narrow to do so and in some cases by ignoring experimental laboratory data altogether. These attemps, though noble in intent, have resulted in several misinterpretations in the literature, especially for the CS (J:2→1) line. For instance, KLV have taken advantage of an exceptionally narrow CS (J:2→1) line in L1498 together with a set of CCS transitions, also very narrow (typically 0.2 km s^{-1}), to show that the observations of the two molecules could be reconciled only if the CS (J:2→1) line frequency was shifted by +90 kHz from the calculated 97980.95 MHz to 97981.04 MHz. This result was also advocated by Dickens et al. (2000) to shift the velocity position of their CS (J:2→1) line towards L183 (=L134N) reference position to such a position that their $C^{34}S$ (J:2→1) transition corresponds to the left peak of the main isotope line instead of being in between its two peaks. Thus, they concluded that they saw two components instead of a single component with self-absorption as previously, and correctly, claimed by Snell et al. (1982). However, Lee et al. 1999 rediscussed independently the CS (J:2→1) line frequency by comparing it to $C^{18}O$, $C^{34}S$ and N_2H^+ at 3mm towards another pre-protostellar core, L1544 and concluded that the best CS (J:2→1) line frequency could be 97980.95 MHz and Lemme et al. (1995)

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⋆ Based on observations made with the Iram 30-m and the formerly-owned NRAO Kitt Peak 12-m
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report the possible presence of a redshifted peak in L1498 and thus reported the main peak as a blueshifted peak in contradiction with the KLV interpretation. However, only their CS (J:3→2) spectrum shows such a convincing case and their $C^{34}S$ lines yield unclear results.

While making relatively high-frequency resolution and high SNR maps of CO, SO and CS towards L183, we were confronted with the same problem as Dickens et al. (2000) for the central position of L183. However, the KLV option did not seem so obvious to us because our data in L183 does not fit this new frequency everywhere, and because we feared that the KLV data could be flawed by some error, hard or soft, owing to the fact that they were comparing data from different telescopes using different softwares, local oscillators and backend setups. We thus chose to re-observe the same source, L1498, but we decided to compare first the CS (J:2→1) line at 98 GHz with the CCS (J_N:$8_7 \rightarrow 7_6$) line at 94 GHz despite the fact that the latter is four times less accurately determined than its lower counterpart at 22 GHz, but still 2.5 times better than CS at 98 GHz (see KLV for more details). This has the advantage that the observations are done with the same telescope, the same receivers from end-to-end and same software, therefore eliminating the possibility of errors associated with either software or hardware.

In this paper, we present the observations in Sect.2 and discuss their interpretation in Sect.3.

2. Observations

2.1. L183

L183 reference position is α_{1950} : $15^h51^m30^s$, δ_{1950} : $-2°43'30"$. All observations presented here have been performed with the Kitt Peak 12-m telescope from Dec. 1999 to June 2000 during its last year under NRAO control. We have been using the 2 and 3 mm receivers. Each mm band is equipped with two mixers in orthogonal linear polarizations working at the same frequency. The backend employed was the Millimeter AutoCorrelator (MAC), and observations were done in frequency switching mode. The MAC initial sampling was set to either 6 or 12 kHz. Pointing was regularly checked towards 3C273, 3C279 or Venus when available. It was found to be very stable, within a few arcseconds. System temperatures (though not relevant here) were ranging from 160 K for frequencies below 100 GHz up to 300 K at 110 GHz and from 300 to 500 K for frequencies in the 2 mm band. To keep the highest frequency resolution possible together with narrow, optically thin and therefore weak lines, we have summed together spectra over a large area (-3′,3′)×(-1′,4′) in relative R.A.-Dec coordinates (except for $C^{34}S$ (J:3→2) which was observed in only 3 positions). This has the advantage that in the absence of velocity changes across the cloud, the mean CS (J:2→1) line is narrower than towards the reference and close nearby positions where this line is somewhat broadened by heavy optical thickness. Figure 1 displays all the observed lines. The Y scale is arbitrary; the

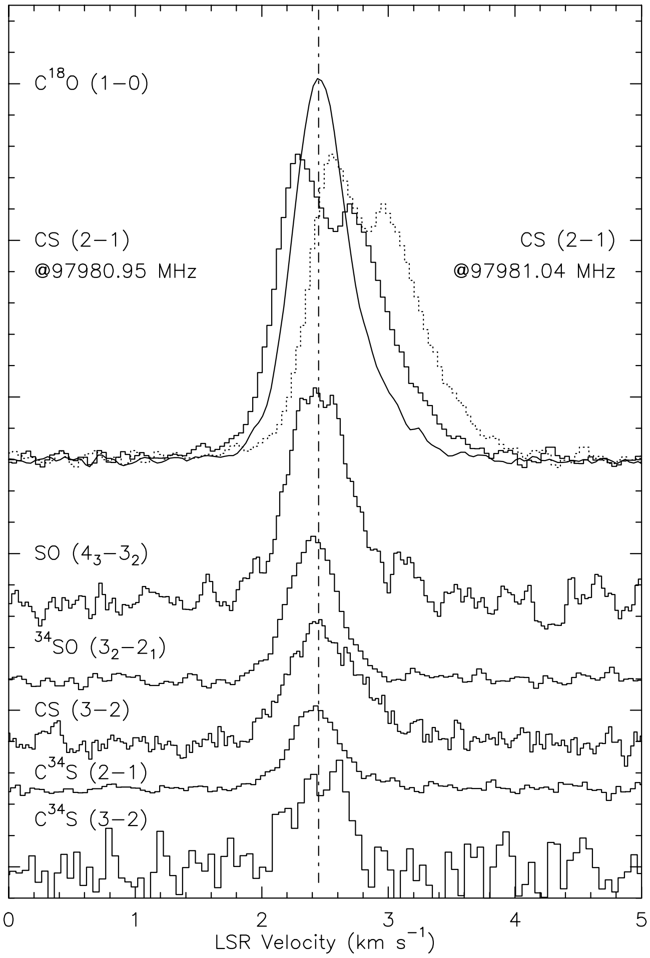

Fig. 1. L183 average spectra for different species and transitions. CS (J:2→1) line has been displayed with the two proposed frequencies (plain line for standard frequency, dashed line for KLV frequency). Despite its larger width compared to $C^{18}O$, the line seems to fit better with the standard frequency. CS($J: 2 \rightarrow 1$)and$^{34}SO(J_N: 3_2 \rightarrow 2_1)$ have been observed simultaneously with the same receiver. Y scale is arbitrary

spectra are scaled and offset such that the lines can be more easily compared.

Fortunately, the CS (J:2→1) line could be observed simultaneously with the $^{34}SO(J_N: 3_2 \rightarrow 2_1)$ line within the same 3 mm receivers. Thus any error (soft or hard) on the sky frequency or on the frequency downward conversion must be the same for these two lines. One should note that the $^{34}SO(J_N: 3_2 \rightarrow 2_1)$ line is actually aligned with the other lines in Fig. 1.

2.2. L1498

Observations of L1498 (α_{1950} : $4^h07^m56^s$, δ_{1950} : $25°01'30''$) were performed at Iram 30-m the 28/05/2001 for the CS (J:2→1) and CCS (J_N:$8_7 \rightarrow 7_6$) lines towards the reference position. On a second run, the 9/8/2001, small maps of the CCS (J_N:$8_7 \rightarrow 7_6$), CS (J:2→1) and (J:5→4) and $C^{34}S$ (J:2→1) have been made. All observations have been performed in frequency switching mode.

Table 1. Observational Parameters

Molecule	*Transition*	*Frequency* (MHz)	*Vel.resol.*[a] (ms^{-1})	*Beamsize* $(arcsec)$
CCS^{I}	J_N:$8_7 \to 7_6$	93870.107	31	25
$C^{34}S$	J:$2 \to 1$	96412.950	38	60
$C^{34}S^{I}$	J:$2 \to 1$	96412.950	60	24
^{34}SO	J_N:$3_2 \to 2_1$	97715.388	37	60
$C^{32}S$	J:$2 \to 1$	97980.950	37	60
$C^{32}S^{I}$	J:$2 \to 1$	97980.950	30/60	24
$C^{18}O$	J:$1 \to 0$	109782.163	33	54
^{32}SO	J_N:$4_3 \to 3_2$	138178.648	26	44
$C^{34}S$	J:$3 \to 2$	144617.110	50	41
$C^{32}S$	J:$3 \to 2$	146969.033	25	41
$C^{32}S^{I}$	J:$5 \to 4$	244935.55	24	12

[a] Final velocity resolution for data display
[I] IRAM 30-m telescope, NRAO 12-m otherwise

System temperature was 100 to 150 K (3 mm lines) and 300 to 400 K (1.3 mm line). Pointing was checked in continuum towards 0234+285 and K3-50. The backend was the autocorrelator with 10 kHz sampling on the first run (2 receivers) and 20 kHz sampling on the second run (4 receivers). Figure 2 displays all the lines on a single axis by applying a suitable offset to the data.

In contrast to the 12-meter observations, those at the 30-m had to be conducted in two steps for the first run : first, the two lines were observed simultaneously with receivers A100 and B100 with CS being in A100 and CCS in B100; and second, the frequencies were swapped with CS in B100 and CCS in A100. No difference at all was found between receivers for the same line. We are thus confident that all possible errors if any are the same for both lines and thus cancel out. Finally spectra from the two receivers were merged together. The final SNR is about 100. The second run was done with CS (J:2→1) in A100, CCS in B100 and CS (J:5→4) in both A230 and B230 (first map) with 20" beam steps and with C^{34}S (J:2→1) instead in both A100 and B100 (A230 and B230 unchanged, second map) with 10" sampling in the central part of the first map. Table 1 gives important observational parameters.

3. Discussion

3.1. L183

Fig. 1 clearly shows that the KLV chosen frequency can not adequately explain the observed data in L183. In fact, after closer examination we have determined that the standard frequency first established by Lovas (1985) and most recently by Gottlieb et al. (2001, 97980.953 ±0.002 MHz) is in perfect agreement with our observations. The fact that the dip in the CS (J:2→1) line is not aligned with the C^{34}S (J:2→1) is not a problem. The self-absorption comes from the envelope of the cloud and can be redshifted in velocity if the envelope is slowly contracting which is not uncommon in observations. On the other hand, trying to align the C^{34}S peak with the C^{32}S leftmost peak would make the C^{32}S and C^{18}O lines only partly overlap each other and indicate through the secondary CS peak the existence of a second CS clump for which no hint of C^{18}O nor C^{32}S (J:3→2) individual peak emission can be seen. The C^{32}S (J:1→0) spectrum towards the center position in Dickens et al. (2000) is also devoid of a secondary velocity peak. While this can be understood in terms of opacity effects (the J:2→1 transition is optically thicker than either the J:1→0 or the J:3→2 transitions), it is difficult to explain these different shapes (1 peak or 2 peaks) in terms of individual components emitting mostly in the J:2→1 transition. Similarly, the linewidth is maximum for the CS (J:2→1) line which confirms the large opacity effect.

3.2. L1498

The first interesting result is that the CS (J:2→1) line frequency correction proposed by KLV, if real, is too large by a factor of 2. The second result is that with good SNR, a Gaussian fit is only marginally possible with the CCS line (which shows signs of slight saturation) and totally impossible with CS (J:2→1). Thus frequency alignment with the CCS line should be considered very cautiously here. Indeed, Lemme et al. (1995) report that the CS (J:2→1) and (J:3→2) transitions show double peak structure, although only the latter shows this feature convincingly. We have thus returned to the 30-m to make a small map to search for convincing CS (J:2→1) double peak profiles and took advantage of the 4 channels capability of the telescope to observe C^{34}S (J:2→1) and CS (J:5→4) transitions, supposedly optically thin, to help understanding the origin of the CS (J:2→1) profile. Though most of the CS (J:2→1) show this typical asymmetric profile, we have found 4 positions (and marginally a fifth one) with double peak profile. The 4 positions, averaged together are shown in Fig.2. The strong CS (J:2→1) peak towards the reference position is thus clearly a blueshifted peak. Whether this profile is due to strong self-absorption or macroscopic movements (infall and/or rotation) is yet unclear. A redside component in both CS lines is traceable by a red wing up to 8.5 km s^{-1}. It, therefore, could absorb the expected redside peak of a strongly self-reversed profile, and explain the dissymmetry of the line. The C^{34}S (J:2→1) line shows a single peak and would suggest self-absorption while the CS (J:5→4) profile suggests a double-peak structure. Again, this could be due to self-absorption or macroscopic movements. For both transitions, SNR is too low on individual spectra to search for macroscopic movements across the map and new observations are needed here. Lee et al. (1999) suggest that in many starless cores, the CS (J:2→1) is slightly blueshifted with respect to N$_2$H$^+$ and traces infall. L1498 obviously is one of their candidates. Finally, infall and/or rotation combined with strong self-absorption could explain this peculiar shape. The redshifted component of the large scale motion could be absorbed by the extra gas which we detect in the red wing.

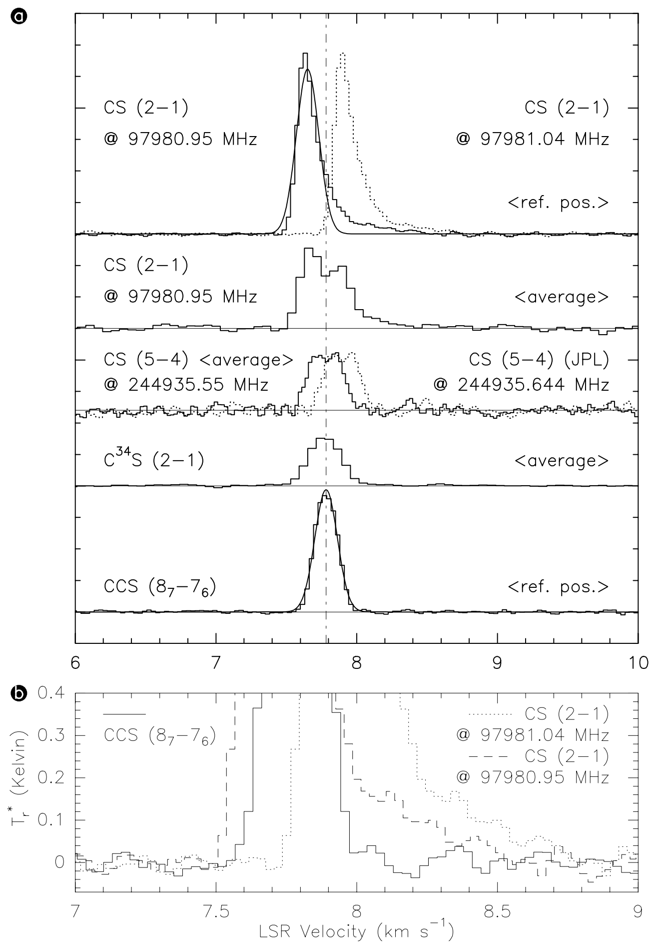

Fig. 2. ab L1498 spectra. **a** As in Fig. 1, Y scale is arbitrary. Tentative Gaussian fits are displayed for the reference position spectra. The CS line profile deviates significantly from Gaussian and is closer to a triangular shape. The CS (J:2→1) line average is a selection of 4 positions in the map with double peak structure while the CS (J:5→4) and $C^{34}S$ (J:2→1) have been averaged over the entire map. **b** Enlargement of the bottom part of the CCS and CS lines (ref. pos.). The Y scale is identical for both lines

Another point is worth mentioning. If one considers only the bottom part of the CS and CCS lines (Fig. 2b), the CS line overlaps fully the CCS line only if we keep the standard CS frequency. We believe that this should have been an argument enough to prohibit changing the frequency of CS to the KLV value even in this cloud.

3.3. $C^{34}S$ (J:2→1) and CS (J:5→4) frequencies

To compare these two rather weak transitions with CCS, we have averaged them all over the map. We think this does not change our conclusions because the strong and narrow blueside CS (J:2→1) peak shows no sizeable velocity displacement across our map. To align the $C^{34}S$ (J:2→1) and the CS (J:5→4) lines on the CCS line (Fig. 2a) we have been obliged to change their frequency. We have also checked that this alignement was compatible with the average CS (J:2→1) spectrum set to the standard frequency.

For $C^{34}S$ (J:2→1), the change is minor (96412.95 MHz instead of 96412.982 ± 0.013 MHz from the Lovas catalogue or 96412.940 ± 0.050 MHz from the JPL catalogue (1985)) and well within the error bars. It perfectly agrees with Gottlieb's reported value of 96412.952 ± 0.002 MHz.

For CS (J:5→4), the discrepancy is noteworthy. While Lovas catalogue indicates 244935.606 ± 0.033 MHz, the JPL catalogue gives 244935.6435 ± 0.0179 MHz and we find 244935.55 MHz. Our value is compatible within the error bar with Lovas catalogue but is 93.5 kHz away from JPL value with a significant 5.2 σ deviation. As our CS (J:5→4) observations have no CCS lines at 1.3mm to be compared to (by lack of observing time) we first suspected a small LO error in the 1.3 mm receivers but the Gottlieb et al. (2001) value plainly confirms our interpretation and the correct LO setup of Iram 1.3 mm receivers. They find 244935.555 ± 0.003 MHz.

4. Conclusions

1. L183 (=L134N) results are not compatible with the KLV CS (J:2→1) line frequency
2. L1498 CS(J:2→1) line frequency is not compatible with the standard frequency if we suppose the line peak to be at the systemic source velocity but the peculiar lineshape indicates physical effects which can explain the difference by radiative transfer effect and/or macroscopic Doppler shift effect (rotation and/or infall)
3. If we limit ourselves to the bottom part of the CS and CCS lines in L1498, then only the standard CS frequency allows a complete overlap of the two lines.
4. Renewed laboratory measurements yield frequencies of 96412.952 ± 0.002 MHz for $C^{34}S$ (J:2→1), 97980.953 ± 0.002 MHz for CS (J:2→1) and 244935.555 ± 0.003 MHz for CS (J:5→4)—in excellent agreement with our interpretation and in disagreement with the JPL catalogue for the latter value.

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