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The $C^{18}O/C^{17}O$ ratio in the Large Magellanic Cloud

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Abstract. We report detections of J=2–1 line emission from the carbon monoxide isotopomers ^{13}CO, $C^{18}O$ and $C^{17}O$ in the molecular clouds N159W, N113, N44BC, and N214DE in the Large Magellanic Cloud (LMC). ^{13}CO and $C^{18}O$ lines were observed in two additional clouds: N159S in the LMC and N27 in the Small Magellanic Cloud (SMC). While ^{13}CO was detected in both of them, only upper limits to the $C^{18}O$ line emission were obtained. Statistical-equilibrium excitation and radiative transfer calculations were made to infer molecular column densities from the observed line intensities. We estimate an average gas-phase $C^{18}O/C^{17}O$ abundance ratio of 1.6±0.3 in the LMC. This is significantly lower than typical values found in Galactic clouds (by a factor of two) and in centres of starburst galaxies (by a factor of five). We use the $C^{18}O/C^{17}O$ abundance ratio as a measure of the elemental $^{18}O/^{17}O$ abundance ratio. Provided that current theories of the nucleosynthesis involving $^{17,18}O$ apply, then the low $^{18}O/^{17}O$ ratio suggests that massive stars have contributed little to the metal enrichment of the interstellar medium in the LMC in the past. This may be caused by a steep initial mass function (which appears to be the case for field stars in the Magellanic Clouds and in the Galaxy) together with a low average star-formation rate. This explanation contrasts with the present situation in prominent star-formation regions in the LMC, such as 30 Doradus, which form stars at a considerable rate and appear to have initial mass functions similar to star clusters in the Galaxy. The apparent spatial constancy of the $^{18}O/^{17}O$ abundance ratio, the nominal values for the individual clouds vary between 1.6 and 1.8, indicates a well mixed interstellar medium and/or that the star-formation activity took place globally in the LMC in the past. In the SMC we obtained a lower limit of 17 for the $^{13}CO/C^{18}O$ ratio (the LMC average is 30), possibly indicating a low ^{18}O abundance here as well. Our data suggests a correlation between the $^{18}O/^{17}O$ abundance ratio and the metallicity. The high $^{18}O/^{17}O$ abundance ratio in centres of starburst galaxies could reflect a high metallicity, mainly caused by a high star-formation rate, possibly but not necessarily together with an initial mass function biased towards massive stars.

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1. Introduction

The chemical evolution of a galaxy is expected to be reflected in the chemical composition of its interstellar medium (ISM). Past stellar generations have left traces of themselves in the ISM by enriching it with stellar processed material via stellar winds and supernova explosions. Massive stars with high mass loss rates will affect the ISM on shorter time scales and more dramatically than low-mass and intermediate-mass stars. An example of such an influence by stars on the ISM is the abundance ratios of isotopes, e.g. $^{18}O/^{17}O$. Since the various oxygen isotopes are believed to originate from different nucleosynthesis processes, these may put useful constraints on nucleosynthesis-schemes, as well as on stellar and galactic evolution models. According to current understanding of stellar nucleosynthesis, ^{18}O, together with the common isotope ^{16}O, are mainly produced from ^{14}N and ^{12}C, respectively, in the helium-burning phase in massive stars. Whereas ^{17}O results from hydrogen-burning in the ON-cycle in intermediate-mass and massive stars (e.g. Prantzos et al. 1996).

To date, the $^{18}O/^{17}O$ abundance ratio has been estimated for the solar system (ratio≈5.5; see e.g. Wilson & Rood 1994), Galactic ISM (≈3.6; Penzias 1981), atmospheres of Galactic red giant stars (≈1; Harris et al. 1988 and references therein; Smith & Lambert 1990), carbon-rich circumstellar envelopes (<1; Kahane et al. 1992), oxygen-rich circumstellar envelopes (≈1; Kahane, priv.comm.), one molecular cloud in the Large Magellanic Cloud (≈2; Johansson et al. 1994), and centres of a few, nearby starburst galaxies (>8; Sage et al. 1991; Henkel & Mauersberger 1993). The discrepancy between the solar system and the interstellar values is a long-standing and still unsolved problem.

In the atmospheres and circumstellar envelopes of stars on the Red Giant Branch (RGB) and the Asymptotic Giant Branch (AGB), the low $^{18}O/^{17}O$ abundance ratio is considered to be caused by transport of ^{17}O-rich material produced in the CNO-cycle up to the stellar surface in dredge-up events following the helium core flash (e.g. Harris et al. 1988; Boothroyd et al. 1994; Forestini & Charbonnel 1997); perhaps in connection with hot bottom burning and cool bottom processing (Boothroyd et al. 1995; Wasserburg et al. 1995). To explain the high $^{18}O/^{17}O$ ratio in the centres of starburst galaxies, Sage et al. (1991) and Henkel & Mauersberger (1993) suggested, in-line with other studies (e.g. Rieke et al. 1980, 1993), that the star-formation activity in such an environment results in an initial mass function (IMF) that is biased towards massive stars. Model calculations by Padoan et al. (1997) suggest that a higher gas temperature leads to a flatter IMF and a higher low-mass cut-off, and accordingly a larger fraction of massive stars. Also the study by Elmegreen (1997) indicates an increasing low-mass cut-off with increasing temperature. However, the existence of and need for a truncation of the IMF at low masses is still unclear (e.g. Zinnecker 1996). Nucleosynthesis models seem to support the notion that massive stars yield a high $^{18}O/^{17}O$ abundance ratio (Weaver & Woosley 1993).

The Large and the Small Magellanic Cloud (LMC and SMC) offer a possibility to study stellar and interstellar processes in an environment quite different from that in the Galaxy. The Magellanic Clouds have low heavy-element contents (metallicities) and dust-to-gas ratios, and intense far-UV radiation fields. The low metallicities of the Magellanic Clouds (MCs) imply that their interstellar media are chemically less processed, and accordingly they are believed to be less evolved than the Galaxy. This is also indicated by the high gas-to-total mass fraction in the MCs. The reason for this is still unclear. The star-formation rate and/or the star-formation efficiency in the MCs have apparently been low during long periods in the past.

Due to the aforementioned effects, the nature of interstellar gas clouds in the LMC and the SMC may differ considerably from Galactic clouds. Since stars form from interstellar molecular gas, differences in the chemical and physical properties of the gas may influence the characteristics of the formed stars. Recent studies of the molecular ISM in the 30 Dor and the N159 areas in the LMC indicate fractional molecular abundances that are significantly lower ($\approx$ a factor of 10) than in Galactic disc clouds. In contrast, all estimated gas-phase isotope ratios in the LMC, except $^{18}O/^{17}O$ and possibly D/H, remain 'Galactic' (cf. Johansson et al. 1994; Chin et al. 1996).

Here we have investigated whether the $C^{18}O/C^{17}O$ ratio is globally low in the LMC. In addition we have observed one cloud in the SMC to compare the LMC and the SMC. As diagnostics we chose the J=2–1 lines of $C^{18}O$ and $C^{17}O$. For completeness we also measured the ^{13}CO J=2–1 line. The motivation for the choice of the J=2–1 transition instead of the J=1–0 is threefold: (1) the excitation conditions in the actively star-forming clouds in the LMC favour the J=2–1 transition in the CO isotopomers, in contrast to molecules with higher electric dipole moments, where higher transitions are generally weaker (Johansson et al. 1994; Heikkilä et al. 1998); (2) the smaller beam-width at the J=2–1 line frequency results in a higher degree of beam-filling, increasing the intensity of the observed line; (3) optically thin J=2–1 lines lines of carbon monoxide isotopomers more accurately determine total column densities (see e.g. Rohlfs & Wilson 1996).

Table 1. Source coordinates

Cloud	α(1950.0)	δ(1950.0)
N159W	$05^h40^m03.0^s$	$-69°47'03''$
N159S	$05^h40^m27.1^s$	$-69°52'00''$
N113	$05^h13^m38.7^s$	$-69°25'57''$
N44BC	$05^h22^m10.6^s$	$-68°00'32''$
N214DE	$05^h40^m36.3^s$	$-71°11'30''$
N27	$00^h46^m32.9^s$	$-73°21'50''$

2. The observed sources

All the clouds we observed in the LMC are among the strongest CO line emitters in this object (Israel et al. 1993). They exhibit prominent star-formation activity, except N159S which appears to be a quiescent cloud. The N159 area is located south of 30 Dor, N214DE even further south of 30 Dor, N113 in the LMC bar, and N44BC near the kinematical (radio) centre. For the locations, see the 12′ resolution CO J=1–0 map by Cohen et al. (1988). N27 is an active star-forming region situated in the gas-rich end of the SMC bar. It has the highest observed integrated CO J=1–0 intensity in the SMC (Israel et al. 1993). The source coordinates are tabulated in Table 1.

3. Observations

The observations were carried out in December 1996 and August 1997 with the SEST[1] at La Silla, Chile. The receiver was a cryogenic 1.3mm SIS mixer, tuned to single-sideband mode and connected to an acousto-optical spectrometer (AOS). The AOS has 1440 channels and a total bandwidth of 1 GHz. The channel-width is $\approx$0.95 km s^{-1} at 220 GHz. Each line was measured separately. Dual beam-switching with a beam-throw of $\approx 12'$ in azimuth was used. The intensity calibration was done with the chopper-wheel method. For the LMC, pointing and focus checks were made at the beginning and end of each day. The stellar SiO masers AH Sco and R Dor, and the Orion KL SiO maser were used as pointing sources. The favourable weather conditions in December 1996 resulted in a system temperature of $\approx$200 K (on the T_A^* scale) and a good and stable pointing, the errors being typically $< 2''$ (rms) in each coordinate. In August 1997 the weather conditions were somewhat poorer, the system temperature was 300–500 K and the pointing errors 2-4″ (rms). Frequent intensity checks were made by observations of the CO and ^{13}CO J=2–1 lines in the N27 cloud in the SMC and the CO J=2–1 line in the N159W cloud in the LMC. Within

[1] The Swedish–ESO Submillimetre Telescope is operated jointly by ESO and the Swedish National Facility for Radio Astronomy, Onsala Space Observatory, at Chalmers University of Technology.

each of the observing runs, only small day-to-day variations in the intensities were discernible. However, differences exist in the absolute intensities when the two sessions (December 1996 and August 1997) are compared. The integrated intensities of the ^{13}CO J=2–1 line turned out to be $\approx$ 35% higher in August 1997 than in December 1996. This applies to all sources. On the other hand, the differences in the $C^{18}O$ and $C^{17}O$ J=2–1 lines (re-observed in August 1997 in N159W, N113 and N44BC) were less than 20% and did not show any clear trend.

The likely explanation for the differences in the ^{13}CO J=2–1 line intensities is non-optimal suppression of the image-band at this frequency (220.4 GHz) in December 1996. The settings for the 1.3mm receiver were adjusted in March 1997, since the image-band suppression had turned out to be non-optimal at several frequencies. While no information is available for the image-band suppression in the 1.3mm receiver for the December 1996 receiver settings, since March 1997 it is measured to be 15 dB or better. In August 1997 we made intensity checks of the observed lines towards the Galactic sources Orion KL and M17SW. The observed ^{13}CO and $C^{18}O$ J=2–1 line intensities were within 15% of calibration observations made by the SEST staff. No previous calibration spectra existed for the $C^{17}O$ J=2–1 line. We measured average $C^{18}O/C^{17}O$ J=2–1 integrated intensity ratios of 4.7 and 3.2 in Orion KL and M17SW, respectively. The corresponding $^{13}CO/C^{18}O$ J=2–1 integrated intensity ratios were 6.6 and 4.2, respectively. The numbers for Orion are consistent within the error estimates with the results of the spectral scan in the 1.3 mm band by Sutton et al. (1985).

Since we will concentrate on intensity *ratios* between different lines, the relevant uncertainties to consider in the total error budget are those introduced by possible pointing and focus drifts during the observations of one particular source. Judging from the results of the pointing and focus tests within each observing run, we estimate the uncertainties in the intensities to be $\pm$10%. However, to account for the problems with the image-band suppression in December 1996, we increase the estimated uncertainty in the intensities to $\pm$20%. The total uncertainty is obtained by adding quadratically the contribution of noise in the spectra. The total uncertainty for an intensity ratio is then typically $\approx \pm$30–35%.

4. Results

The observational results are shown in Tables 2–3 and in Fig. 1. For ^{13}CO we have recalibrated the December 1996 data to agree with the August 1997 data by applying a correction factor of 1.35 before adding the data-sets taken during the two sessions. The presented $C^{18}O$ and $C^{17}O$ data are straight averages of the two sessions. Table 2 presents the line parameters from fits of Gaussian line profiles to the measured spectra. First order baselines were subtracted from the spectra in the data-reduction. The upper limits for the integrated intensity of $C^{18}O$ in the N159S and N27 clouds were calculated as $T_{\rm pp}\Delta v$, where $T_{\rm pp}$ is the peak-to-peak channel-noise in a spectrum which has been smoothed to a channel-width equal to the expected full-width at half-maximum (FWHM) line-width, Δv (taken as 6.3 and 3.8 km s^{-1} in N159S and N27, respectively). The intensities are given in the main-beam brightness temperature scale ($T_{\rm mb} = T_{\rm A}^*/\eta_{\rm mb}$, where $\eta_{\rm mb}$ is the main-beam efficiency of the telescope: 0.61 at 220 GHz). The tabulated channel-noises ($T_{\rm rms}$) and uncertainties in the integrated intensities ($I_{\rm rms}$) are defined by 2σ rms noise fluctuations. The rms noise in the integrated intensity was calculated using the expression $I_{\rm rms}$=$\sqrt{n_{\rm chan}}\Delta v_{\rm chan}T_{\rm rms}$, where $n_{\rm chan}$ is twice the FWHM line-width in number of channels, $\Delta v_{\rm chan}$ is the channel-width in km s^{-1}, and $T_{\rm rms}$ is the channel-noise (2σ rms). Table 3 displays the integrated intensity ratios. Since the telescope beams at the frequencies of the ^{13}CO, $C^{18}O$, and $C^{17}O$ lines are in practice identical, no correction due to beam-dilution was necessary. The quoted errors are given as described in Sect. 3. The observed spectra are displayed in Fig. 1. The velocity scale is relative to the local standard of rest (LSR).

The column densities of the various carbon monoxide isotopomers were estimated from the observed line intensities using two methods: (1) assuming local thermodynamic equilibrium (LTE), i.e. a uniformly excited and Boltzmann distributed population of the rotational energy levels, and low optical depths (see e.g. Turner 1991); (2) applying a statistical-equilibrium excitation and radiative transfer code. In the latter method the model cloud was spherical with a constant temperature and density, and the radiative transfer was treated in the mean escape probability (MEP) approximation, see e.g. Jansen (1995). Identical collision coefficients, taken from Schinke et al. (1985) and Flower & Launay (1985), were used for the various CO isotopomers. The hyperfine structure of $C^{17}O$ was not taken into account explicitly, instead the hyperfine components for a specific $J \rightarrow J-1$ transition were treated as a single line. The ambient radiation field was taken to be the cosmic background radiation, i.e. a black body at a temperature of 2.73 K. In the LTE calculations the excitation temperature was varied between 10 and 30 K. The resulting column density ratios were practically insensitive to the variation in the excitation temperature. The tabulated LTE results are averages of the values obtained for 10 K, 20 K and 30 K. In the MEP calculations the column density of a molecule 'mol' per unit line-width ($N_{\rm mol}/\Delta v$) was determined by varying it until the brightness temperature of the model cloud was equal to the observed main-beam brightness temperature, while keeping the number density and the kinetic temperature fixed at the values given in Table 4. The column density was obtained by multiplying $N_{\rm mol}/\Delta v$ with the observed FWHM line-width. The temperatures and the densities used for the N159W, N159S, and N27 clouds were taken from Heikkilä et al. (1998), where detailed excitation and radiative transfer calculations using several molecules and transitions for these clouds were performed. For the remaining LMC sources with detected $C^{18}O$ and $C^{17}O$ emission we used a kinetic temperature of 20 K, taken from Chin et al. (1996), while the gas densities were estimated from an excitation analysis of our own (unpublished) CS and SO multi-transition data. Table 4 indicates that the physical conditions in these clouds do not differ considerably from those in N159W. The column density ratios obtained using the MEP code do not change significantly when the density and the temperature are varied in the intervals 10^4–

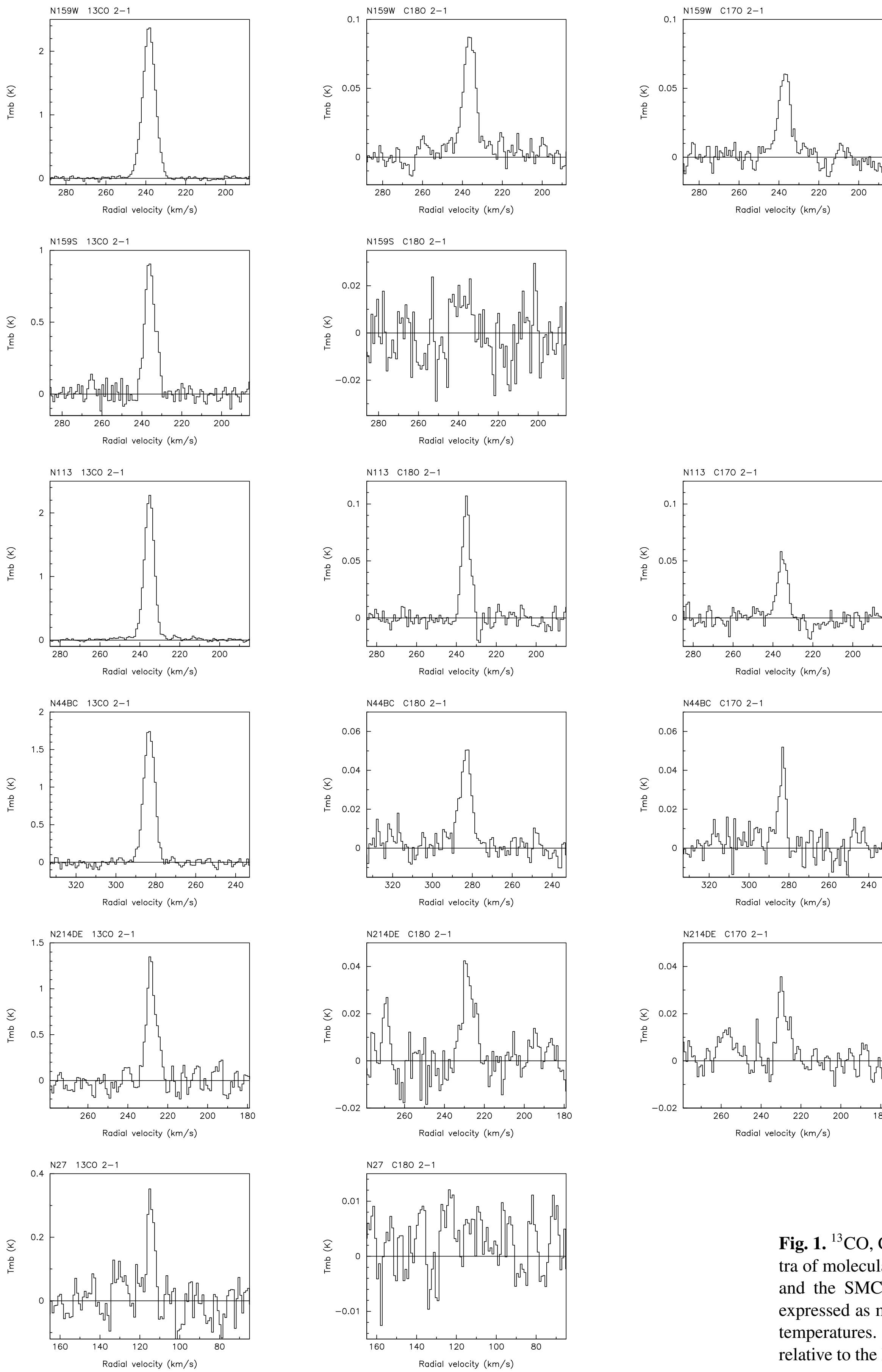

Fig. 1. ^{13}CO, C^{18}O, and C^{17}O spectra of molecular clouds in the LMC and the SMC. The intensities are expressed as main-beam brightness temperatures. The velocity scale is relative to the local standard of rest.

Table 2. Line parameters of the observed spectra

Source	Molecule	Transition	T_{mb} [K]	v_{LSR} [km s^{-1}]	Δv [km s^{-1}]	$I_{mb}^{a)}$ [K km s^{-1}]	$T_{rms}^{b)}$ [K]
N159W	^{13}CO	J=2–1	2.34	238.4	7.5	18.6(0.18)	0.046
	$C^{18}O$	J=2–1	0.088	236.4	7.4	0.70(0.048)	0.013
	$C^{17}O$	J=2–1	0.061	237.2	7.0	0.46(0.042)	0.012
N159S	^{13}CO	J=2–1	0.89	235.9	6.3	5.96(0.39)	0.11
	$C^{18}O$	J=2–1	-	-	-	$<$0.24	0.016
N113	^{13}CO	J=2–1	2.26	235.2	5.8	14.0(0.17)	0.049
	$C^{18}O$	J=2–1	0.100	235.1	4.8	0.51(0.041)	0.013
	$C^{17}O$	J=2–1	0.055	235.2	5.8	0.34(0.038)	0.011
N44BC	^{13}CO	J=2–1	1.78	283.3	6.4	12.2(0.36)	0.10
	$C^{18}O$	J=2–1	0.049	283.3	6.8	0.35(0.039)	0.011
	$C^{17}O$	J=2–1	0.046	283.2	4.0	0.20(0.038)	0.014
N214DE	^{13}CO	J=2–1	1.30	228.0	5.7	7.88(0.69)	0.21
	$C^{18}O$	J=2–1	0.037	228.1	7.4	0.30(0.058)	0.015
	$C^{17}O$	J=2–1	0.030	229.4	6.3	0.20(0.041)	0.012
N27	^{13}CO	J=2–1	0.34	114.5	3.9	1.44(0.31)	0.11
	$C^{18}O$	J=2–1	-	-	-	$<$0.084	0.0094

$^{a)}$ The numbers given in brackets are 2σ noise fluctuations in the integrated intensity
$^{b)}$ The channel-noise at 2σ level

Table 3. Integrated intensity ratios

Molecules	N159W	N159S	N113	N44BC	N214DE	N27
$^{13}CO/C^{18}O$	27±8	>24	27±9	35±11	27±10	>17
$^{13}CO/C^{17}O$	41±13	-	41±13	62±22	40±15	-
$C^{18}O/C^{17}O$	1.5±0.5	-	1.5±0.5	1.8±0.7	1.5±0.6	-

Table 4. Physical conditions

Parameter	N159W	N159S	N113	N44BC	N214DE	N27
$n(H_2)$ [cm^{-3}]	5×10^5	5×10^4	5×10^5	5×10^5	5×10^5	5×10^4
T_{kin} [K]	25	10	20	20	20	15

Table 5. Main-beam averaged column densities

Molecule	N159W	N159S	N113	N44BC	N214DE	N27
^{13}CO	1.1(16)	4.3(15)	8.3(15)	7.1(15)	4.6(15)	7.9(14)
$C^{18}O$	4.0(14)	<1.7(14)	2.8(14)	2.0(14)	1.7(14)	<4.6(13)
$C^{17}O$	2.6(14)	-	1.8(14)	1.1(14)	1.1(14)	-

$a(b)$ denotes $a \times 10^b$ [cm^{-2}]
The uncertainties are 25-35 %.

Table 6. Column density ratios

Source	^{13}CO/C^{18}O	^{13}CO/C^{17}O	C^{18}O/C^{17}O
N159W[1]	26±8	42±13	1.6±0.5
N159W[2]	28±9	44±14	1.6±0.5
N159W[3]	34	68	2.0±0.5
N159S[1]	>24	-	-
N159S[2]	>26	-	-
N113[1]	27±8	42±13	1.6±0.5
N113[2]	29±9	45±14	1.6±0.5
N113[4]	25	>44	>1.7
N44BC[1]	34±11	63±22	1.8±0.7
N44BC[2]	36±12	66±23	1.8±0.7
N214DE[1]	27±10	41±15	1.5±0.7
N214DE[2]	27±10	43±16	1.6±0.7
N27[1]	>17	-	-
N27[2]	>17	-	-
LMC average[5]	30±5	47±8	1.6±0.3
Galactic ISM[6,7]	6.5	20	3.6
Solar system[7]	5.5	30	5.5
Envelopes of evolved stars[8]	17	15	<1
Atmospheres of red giants[9]	-	-	≈1
Starburst galaxies[7,10]	3–6	20–40	>8

[1]This work, LTE analysis
[2]This work, MEP analysis
[3]J=1–0 data from Johansson et al. (1994)
[4]J=1–0 data from Chin et al. (1997)
[5]J=2–1 data from this work (N159S excluded), MEP analysis
[6]C^{18}O/C^{17}O data from Penzias (1981)
[7]Data from Wilson & Rood (1994)
[8]Kahane et al. (1992) and Kahane (priv.comm.)
[9]Data from Harris et al. (1988) and references therein
[10]Integrated intensity ratios from Aalto et al. (1995) and Johansson et al. (1994)

10^6 cm^{-3} and 10–30 K, respectively. The C^{18}O/C^{17}O ratio is very stable with a variation of $< 2\%$, while the ^{13}CO/C^{18}O and ^{13}CO/C^{17}O ratios vary by $< 15\%$. The column density estimates obtained from the MEP analysis are presented in Table 5. Since the intensities used in the calculations were not corrected for finite beam and source sizes, the tabulated values are main-beam averages. Table 6 contains column density ratios of isotopomers for our sample of clouds (the quoted errors are given as described in Sect. 3.), together with data collected from the literature for Galactic and extragalactic sources.

5. Discussion

Our results for the J=2–1 transitions of C^{18}O and C^{17}O towards four clouds in the LMC confirm and extend the previous J=1–0 observations, which gave a low C^{18}O/C^{17}O ratio (≈2) in the N159W cloud (Johansson et al. 1994). The average C^{18}O/C^{17}O abundance ratio in the LMC, 1.6±0.3, is significantly lower than in Galactic clouds (by a factor of two), the solar system (by a factor of three) and centres of starburst galaxies (by a factor of five). Since the clouds we investigated are located in different parts of the LMC, the estimated C^{18}O/C^{17}O abundance ratios indicate a global underabundance of C^{18}O relative to C^{17}O in the

LMC. Relative to the Galactic ISM, the $^{13}CO/C^{17}O$ abundance ratios (average ≈ 47) in the LMC are 2–3 times higher, while the $^{13}CO/C^{18}O$ ratios (average ≈ 30) are a factor of 4–5 higher. This supports the notion, that the low $C^{18}O/C^{17}O$ ratio reflects an underabundance of $C^{18}O$, rather than an overabundance of $C^{17}O$. Besides, the indicated overabundance of ^{13}CO relative to $C^{17,18}O$ is supported by the low $^{12}CO/^{13}CO$ abundance ratio of 20 found for the N159W cloud (Heikkilä et al. 1998) — where the $^{12}C/^{13}C$ ratio is estimated to be 50 (Johansson et al. 1994). Judging from the strong and extended C^+ line emission in the LMC (Mochizuki et al. 1994; Israel et al. 1996) also $^{13}C^+$ is likely to be ubiquitous, and the increased ^{13}CO abundance in the LMC can be explained by chemical fractionation. On the other hand, a low abundance of $C^{17,18}O$ relative to ^{13}CO could also be caused by selective photodissociation in favour of the latter specimen. For the N159S cloud in the LMC and the N27 cloud in the SMC, only upper limits for the $C^{18}O$ line emission were obtained and no observations of $C^{17}O$ were made. However, the lower limits in N159S (≈ 26) and N27 (≈ 17) for the $^{13}CO/C^{18}O$ abundance ratio are significantly higher than in Galactic clouds and starburst galaxies. Accordingly, a low $C^{18}O$ concentration and, probably, a low $C^{18}O/C^{17}O$ ratio is suggested for these sources as well.

An interpretation of the observations in terms of the properties of the ISM and stellar populations (given in Sect. 5.2) requires that the column density ratio can be safely derived from the intensity ratio, and that it reflects the molecular abundance ratio. Also required is, that the molecular abundance ratio can be directly translated into the elemental isotope ratio. Sect. 5.1 deals with these issues.

5.1. Interstellar processes affecting abundance estimates

Since previous observations indicate that the optical depths of the molecular line emission from the Magellanic Clouds are low (see Johansson et al. 1994), and since we are using a MEP approach in the excitation and radiative transfer analysis, we do not expect, under normal conditions, excitation and optical depth effects to complicate the derivation of the column density ratios from the $C^{18}O/C^{17}O$ intensity ratios. However, the excitation of the hyperfine components of $C^{17}O$ has yet not been investigated in detail in the literature — from neither a theoretical nor an observational point of view. Excitation anomalies among the hyperfine split energy levels, leading to non-LTE population of the energy levels, could affect total column density estimates, resulting in values significantly departing from the traditionally applied LTE case. However, if such an effect exists, it is likely to be present in Galactic clouds as well. In that case our present results concerning a real difference between the LMC and the Galaxy would hardly be affected. Another, possibly more relevant, implication of this kind of anomalous excitation would be, in combination with possible saturation in the $C^{18}O$ lines in Galactic clouds, a smaller discrepancy between the interstellar and the solar system $^{18}O/^{17}O$ ratios.

Next, we turn to fractionation, caused by chemical reactions as well as photodissociation. While carbon ions lead to an efficient fractionation of carbon isotopes in interstellar molecules, analogous reactions involving oxygen ions are not believed to be important (Langer et al. 1984). Moreover, the interstellar abundance of oxygen ions is likely low (the ionisation potential of oxygen is 13.6 eV, in addition O^+ hydrogenates quickly to H_3O^+). Thus, chemical fractionation will hardly affect the $C^{18}O/C^{17}O$ abundance ratio.

Due to the relatively strong far-UV radiation fields and low dust-to-gas ratio in the LMC, fractionation caused by selective photodissociation can be of potential importance. The low column densities of $C^{17}O$ and $C^{18}O$ in the LMC conceivably inhibit differences in their self-shielding ability. Thus, isotopic fractionation of $C^{17}O$ and $C^{18}O$ caused by selective photodissociation due to their *self-shielding ability* is unlikely to occur. However, unlike the other stable isotopomers of CO (e.g. Eidelsberg et al. 1992; Ubachs et al. 1994), spectroscopic data concerning the photodissociation of $C^{17}O$ are not available. Accordingly, a detailed theoretical treatment of the photodissociation of $C^{17}O$ has not yet been done as is the case for the other CO isotopomers (van Dishoeck & Black 1988; Warin et al. 1996). Therefore, it cannot be excluded that overlapping far-UV lines of H, H_2, or ^{12}CO may shield $C^{17}O$ better than $C^{18}O$, and thereby lower the $C^{18}O/C^{17}O$ ratio. In addition, if the interstellar radiation field shows rapid variations with respect to the frequency, fractionation due to photodissociation could occur if the field strengths at the frequencies of the dissociating bands of $C^{17}O$ and $C^{18}O$ differ significantly. White & Sandell (1995) found a weak trend for lower $C^{18}O/C^{17}O$ ratios with decreasing visual extinction in the Orion molecular cloud. This may indicate selective photodissociation in favour of $C^{17}O$. Compared to the Galaxy, photon-dominated regions are more prominent in the LMC (Mochizuki et al. 1994; Israel et al. 1996); hence this type of effect could possibly take place in the LMC.

We now return to a more conservative and traditional view. Based on present knowledge, we do not find strong evidence for effects that selectively affect molecules containing ^{17}O and ^{18}O. Accordingly, we assume below that the $C^{18}O/C^{17}O$ column density ratios listed in Table 6 provide accurate estimates of the $^{18}O/^{17}O$ abundance ratios.

5.2. What does the $^{18}O/^{17}O$ ratio tell us?

If chemical processing in the ISM can be neglected or corrected for, then a measured isotope ratio, such as $C^{18}O/C^{17}O$, can be interpreted in terms of the characteristics of stars in previous stellar generation(s) that dominated the enrichment of the ISM. In the following discussion, we assume that current theories for the nucleosynthesis of $^{17,18}O$ apply.

5.2.1. Metallicity

The low metallicity of the LMC is relevant from several points of view when explaining the low $^{18}O/^{17}O$ abundance ratio.

Although ^{14}N is the main precursor of ^{18}O, the amount of ^{18}O produced in stellar nucleosynthesis is primarily determined by the initial abundances of ^{12}C and to some extent ^{16}O (i.e. by the metallicity of the gas from which the star formed). This is because nitrogen itself is synthesised mainly in the CN-cycle (starting with ^{12}C) and to some extent in the ON-cycle (starting with ^{16}O), see e.g. Prantzos et al. (1996). The ^{17}O abundance is also related to the initial metallicity since it is produced in the ON-cycle. Comparing H II regions in a sample of dwarf galaxies with the Galaxy, Garnett et al. (1995) found that the C/O ratio seems to correlate with the O/H ratio, i.e. with the metallicity if oxygen is a reliable indicator of the metallicity. Moreover, Prantzos et al. (1994) find that [C/O] $\propto$ [Fe/H] for massive stars, if metallicity dependent yields for oxygen and carbon are used.

Provided that the ^{18}O abundance mainly depends on the initial ^{12}C abundance and that the abundance of ^{17}O correlates with that of the initial ^{16}O, and using the empirical relation found by Garnett et al. (1995): [C/O] $\propto$ [O/H], we suggest that the $^{18}O/^{17}O$ abundance ratio is a function of the metallicity, with a decreasing metallicity leading to a decreasing $^{18}O/^{17}O$ abundance ratio. This agrees well with the LMC having a lower $^{18}O/^{17}O$ ratio than the Galaxy and centres of starburst galaxies. The $^{18}O/^{17}O$ ratio has yet not been measured in the SMC. However, due to the even lower metallicity and C/O ratio in the SMC, the $^{18}O/^{17}O$ ratio is then expected to be even lower than in the LMC. Also, the suggested $^{18}O/^{17}O$ – metallicity relation makes sense in the centres of starburst galaxies. A metal-rich ISM will conceivably result from their high star-formation rates (SFRs). Moreover, if the SFR is high enough, the IMF has not necessarily to be biased towards massive stars in order for the massive stars to dominate the enrichment of the ISM during the burst and some time after it.

The study of metal-poor galaxies by Carigi et al. (1995) indicates a larger fraction of less-massive stars in low-metallicity systems. Moreover, in a low-metallicity environment, it is easy to form carbon-stars (e.g. Leisy & Dennefeld 1996) and difficult to form Wolf-Rayet stars (Maeder & Conti 1994). The carbon stars are of special interest, as being major suppliers of stellar processed matter to the ISM via their high mass loss rates. The winds of Wolf-Rayet stars, together with supernova explosions, are the main agents in enriching the ISM with material processed in massive stars. The ratio of carbon stars to M giants (C/M) is much higher in the LMC than in the Galaxy (Blanco & McCarthy 1981), possibly indicating a relatively evolved middle-age stellar population. Brewer et al. (1995) suggest that the C/M ratio depends inversely on the metallicity. Furthermore, the number-ratio of red supergiants to Wolf-Rayet stars increases and the ratio of the Wolf-Rayet subtypes WC/WN decreases in the sequence Galaxy:LMC:SMC (Westerlund 1990; Maeder & Conti 1994), showing that the youngest populations in the Magellanic Clouds are little evolved. Massey & Armandroff (1995) suggest that WC/WN increases with an increasing metallicity and an increasing fraction of massive stars. Hence, the composition of the ISM in the LMC is probably not yet contaminated by the most recent star-formation activity, except possibly in isolated areas such as the 30 Dor nebula. Alternatively, such violent star-formation activity did not take place in the past. The locations of the known supernova remnants are biased towards 30 Dor and the LMC bar (Westerlund 1990).

In conclusion, the low metallicity environment of the Magellanic Clouds seems to provide a favourable framework for obtaining a low $^{18}O/^{17}O$ ratio. Our data suggests a correlation between the $^{18}O/^{17}O$ abundance ratio and metallicity.

5.2.2. Star-formation history

The high gas-to-total mass ratio in the Magellanic Clouds indicates that their mean SFRs and/or star-formation efficiencies (SFEs) have been low. A low *mean* SFR can result from a star-formation activity that is constantly low, or alternatively burst-like with long, quiet periods between the bursts. The low metallicity in the LMC and SMC indicates a slow metal-enrichment of their interstellar media. This is connected to the nature of the SFR and SFE, but also to the IMF and inherent stellar properties. Taken together, *if a sufficiently long time-period is considered and the IMF is not biased towards massive stars (i.e. has a sufficiently steep slope and a low enough low-mass cut-off), the ISM is mainly enriched by low-mass and intermediate-mass stars, and provided current theories on the nucleosynthesis of* ^{17,18}O *are valid a low* $^{18}O/^{17}O$ *ratio will result.* Holtzman et al. (1997) and Stappers et al. (1997) find a relatively steady SFR for field stars outside the LMC bar. Also Feast (1995) favours an LMC star-formation history without bursts. Moreover, the low number of interstellar masers (H_2O, OH, CH_3OH), which are usually present in regions associated with formation of massive stars, found in the LMC may indicate a low SFR (Whiteoak & Gardner 1986, Ellingsen et al. 1994), although the lack of at least methanol masers may also be due to a low abundance of complex molecules caused by the low metallicity (Ellingsen et al. 1994).

The IMFs for star clusters in the Galaxy, the LMC (including 30 Dor), and the SMC have been found to be similar (e.g. Maeder & Conti 1994; Massey et al. 1995a,b; Brandl et al. 1996; Hunter et al. 1997). Hill et al. (1997) inferred from CNO and Fe abundances in stellar atmospheres that the IMFs may well be similar in the Magellanic Clouds and the Galaxy, but that a lower SFR (continuous or burst like) likely applies for the MCs. According to Massey et al. (1995a), differences exist in the slopes for the IMFs when stars in clusters/associations and field stars are compared: the field stars show a steeper IMF. Also in this respect the Magellanic Clouds and the Galaxy behave similarly. This suggests similar present-day mass-distributions for the stellar populations for these three systems. However, the information on the low-mass end ($<$1–2 $M_\odot$) of the IMF in the MCs is still limited. Assuming that clusters mainly form as a result of burst-like star-formation activity, the observed low $^{18}O/^{17}O$ abundance ratio in the LMC may indicate a deficit of star clusters in the past and hence support a star-formation history dominated by relatively quiescent events rather than violent bursts. Moreover, since ^{17}O is considered to be produced in intermediate-mass and high-mass stars, but not in low-mass ($<$1–2 $M_\odot$) stars, where the ON-cycle is not active (Prantzos et al. 1996), and ^{18}O is produced in massive stars, a low $^{18}O/^{17}O$

implies that intermediate-mass stars dominate over high-mass stars in their enrichment of the ISM. These results may indicate a considerably steeper IMF, more similar to that observed for field stars, for the LMC (in the past) than what is presently the case for prominent star-formation regions in the LMC and the Galaxy. This is likely closely connected to a low SFR.

The apparently constant $C^{18}O/C^{17}O$ ratio — the nominal values being 1.6-1.8 — measured in clouds with different spatial locations implies that either the remnants of a number of localised star-formation events have been efficiently dispersed and become well mixed on a large scale, or star-formation must have taken place globally in the LMC. A well mixed ISM is supported by the fact, that LMC contains a bar, a galaxy-component that tends to circulate material. In addition, the small size of the LMC is favourable in obtaining a good mixing. On the other hand, also a global burst of star-formation activity, e.g. induced by an interaction with the Galaxy at a pericentre passage or an LMC-SMC collision, or a large-scale gas instability, could have resulted in a common IMF in the LMC, and accordingly a chemically homogeneous ISM. Age estimates for stellar associations in the LMC show that the present population exhibits similar ages all over the LMC (Westerlund 1990). The same could well have been the case at earlier epochs of star-formation activity.

In conclusion, both a low average SFR and an IMF biased towards low-mass and intermediate-mass stars appear to be required in order to explain a low $^{18}O/^{17}O$ abundance ratio in the LMC.

6. Summary

We have observed and detected J=2–1 line emission from the carbon monoxide isotopomers ^{13}CO, $C^{18}O$, and $C^{17}O$ in four molecular clouds (N159W, N113, N44BC, N214DE) in the LMC. ^{13}CO and $C^{18}O$ were observed in two additional clouds: N159S in the LMC and N27 in the SMC; while line emission from ^{13}CO was detected in both of them, only upper limits to the $C^{18}O$ line emission were obtained.

Our main results are as follows:

1. The gas-phase $C^{18}O/C^{17}O$ abundance ratio in the LMC is estimated to be 1.6±0.3, i.e. significantly lower than in molecular clouds in the Galaxy and centres of starburst galaxies.
2. While the estimated $^{13}CO/C^{18}O$ abundance ratio ($\approx$ 30) is significantly higher in the LMC than in the Galactic ISM and in centres of starburst galaxies, the $^{13}CO/C^{17}O$ abundance ratio ($\approx$ 47) observed in the LMC sources is higher than in the Galactic ISM but possibly comparable to values found for centres of starburst galaxies.
3. In the SMC, only an upper limit to the $C^{18}O$ emission was obtained and $C^{17}O$ was not observed. However, the lower limit of 17 for the $^{13}CO/C^{18}O$ ratio points towards a low ^{18}O abundance here as well.
4. The low $^{18}O/^{17}O$ ratio, inferred from the observed $C^{18}O/C^{17}O$ ratio, is likely related to the low metallicity in the LMC. Closely connected to this is the suggestion that the low oxygen isotope ratio indicates that the ISM in the LMC has been mainly enriched by low-mass and intermediate-mass stars. This could result from a low *average* SFR together with an IMF biased towards low-mass and intermediate-mass stars in the LMC. While the present-day IMFs for stellar clusters/associations in the Galaxy and the Magellanic Clouds show slopes similar to the Salpeter value, steep IMFs have been estimated for field stars in the Magellanic Clouds and the Galaxy by Massey et al. (1995a).
5. If $^{18}O/^{17}O$ depends on $^{12}C/^{16}O$, as suggested by the main formation paths of ^{18}O (via the CN-cycle and subsequent helium-burning) and ^{17}O (in the ON-cycle), then the correlation between [$^{12}C/^{16}O$] and [O/H] found by Garnett et al. (1995), together with the assumption that oxygen is a reliable indicator of the metallicity, suggests that the $^{18}O/^{17}O$ abundance ratio correlates with the metallicity. This would imply an even lower $^{18}O/^{17}O$ abundance ratio for the SMC than in the LMC. Moreover, the high $^{18}O/^{17}O$ abundance ratio in centres of starburst galaxies could reflect a high metallicity, caused primarily by a high SFR, possibly but not necessarily, together with an IMF biased towards massive stars. A biased IMF has been suggested to be the main reason by other authors.
6. The apparent constancy of the $C^{18}O/C^{17}O$ ratio among the four clouds indicates a well mixed ISM, or that the main star-formation events in the LMC have taken place globally.
7. Fractionation caused by selective photodissociation of $C^{17}O$ and $C^{18}O$, or anomalous excitation of the hyperfine components of $C^{17}O$, could modify the estimated $^{18}O/^{17}O$ abundance ratio, and therefore have consequences for the interpretation in terms of the relative number of massive and less-massive stars when explaining the low oxygen isotopic ratio. In the case of anomalous excitation, if it exists, the same effect is likely to be present in both the Magellanic Clouds and the Galaxy. If the interstellar abundance of $C^{17}O$ is overestimated by traditional methods, the $^{18}O/^{17}O$ ratio in Galactic clouds would be more similar to the solar.

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