The interstellar matter of the LMC probed with background AGN X-ray emission

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Abstract

We have investigated the total amount of absorbing gas in a 10°× 10° field of the Large Magellanic Cloud and in the direction of background X-ray sources which we have taken from the *ROSAT PSPC* catalog of Haberl & Pietsch 1999. We constrained for 26 background X-ray sources total absorbing column densities due to LMC gas and compared these columns with the H I columns measured with the *Parkes* radio telescope. We find within the uncertainties agreement for the X-ray derived and the H I columns. For 10 AGN we constrain LMC gas additional to the H I and assuming that it is due to molecular gas we derive upper limits for the molecular mass fraction of <20 to 80%. For the radio source RX J0536.9-6913 located in the 30 Dor complex we derive from the X-ray spectral fit the largest column of $\sim 10^{22}$ cm^{-2}. We also construct the $\log N - \log S$ from an extended sample of candidate AGN behind the LMC in our investigated 10°× 10° field. We take absorption due to LMC gas (the H I) into account and compare our observed $\log N - \log S$ with the $\log N - \log S$ of the soft extragalactic X-ray background derived from fields at a high galactic latitude. The molecular fractions derived from AGNs, and $\log N - \log S$ are very uncertain but they agree with the estimates from CO studies.

1 Introduction

The interstellar medium (ISM) in the Large Magellanic Cloud (LMC) is ideally suited to study star formation and stellar evolution under chemical conditions which differ from that in our Galaxy. The ISM is a thermodynamic system with a variety of thermal phases with different characteristic values of temperatures and densities. There is the cool neutral medium with temperatures of $\sim$(50–120) K and number densities of $\sim (10^{-1}$ to $10^{-2})$ cm^{-3}, intermediate phases of warm ionized gas and warm neutral gas with temperatures of $\sim$(6000 – 12000) K, dense molecular clouds with temperatures of $\sim$(5–10) K and number densities of $\sim 10^3$ cm^{-3} and the hot ionized gas with a temperature of $\gtrsim 10^6$ K and number densities of a few 10^{-3} cm^{-3}.

Studies of the cool neutral phase of the ISM in the LMC (the H I) have been performed by Luks & Rohlfs (1992) and Brüns et al. (2001) with the *Parkes* radio telescope at 21-cm with a resolution of 14′. Dickey et al. (1994) made a 21-cm absorption survey of the Magellanic system with the Australia Telescope Compact Array (*ATCA*) and Kim et al. (1998) obtained aperture synthesis mosaics of the LMC with a resolution of 1′ with *ATCA*. The molecular phase has been investigated in a CO study performed by Cohen (1988) and a ^{12}CO survey with *NANTEN* (cf. Mizuno et al. 1999). UV study of H_2 in the LMC has been performed by Richter (2000). The hot ionized phase of the ISM in the LMC has been observed in soft X-rays during the *ROSAT* all-sky survey (Trümper et al. 1991; Pietsch & Kahabka 1993) and during deep pointed observations (Snowden & Petre 1994, see also Haberl & Pietsch 1999, hereafter HP99). In addition HP99 have derived a catalog of X-ray point sources in the field of the LMC.

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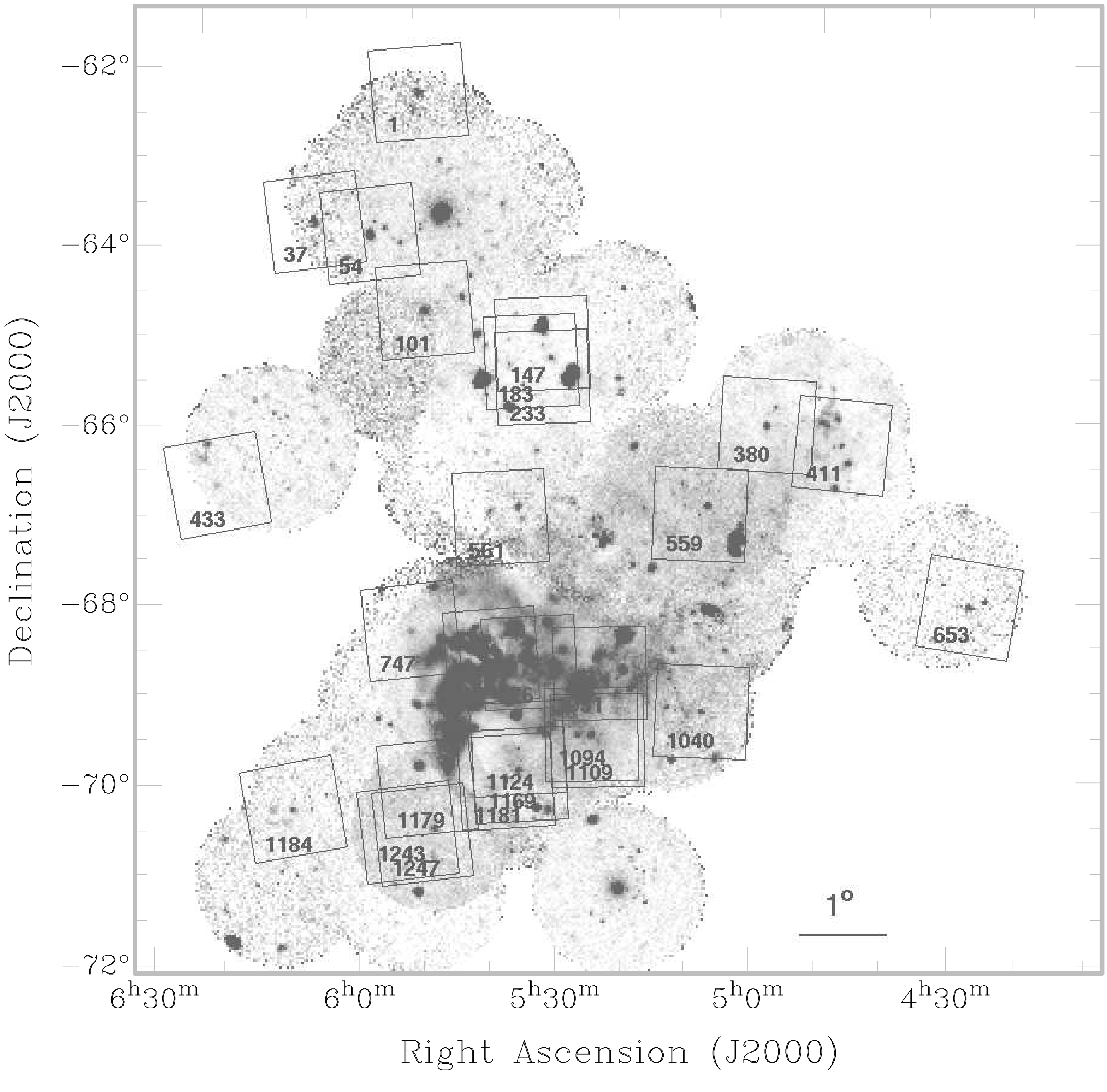

Figure 1: Merged image (533 ksec) of the *ROSAT PSPC* observations of the LMC field. With boxes the 1°× 1° *ROSAT PSPC* fields centered on the AGN (and candidate AGN) are shown. The boxes are labelled with the source number from the catalog of HP99. The image is generated in the energy range (0.4 - 1.3) keV and is corrected for exposure. It shows point like X-ray sources and structure due to the LMC gas. For some detector fields the brightness differs from neighbouring fields due to observation dependent remaining background flux variations (Figure taken from Paper I).

2 Total LMC gas absorption from X-ray spectral fits, comparison with H I , and constraints on molecular gas

Background X-ray sources like Active Galactic Nuclei (AGN) can be used to measure the amount of absorbing matter in a foreground galaxy like the LMC. We selected the AGN (and candidate AGN) used for our analysis of the LMC gas columns (Kahabka et al. 2001, hereafter Paper I) from the *ROSAT PSPC* catalog of X-ray sources in the LMC field (HP99). We used optically identified AGN for which a redshift has been determined (cf. Crampton et al. 1997), further sources for which an identification with an optical galaxy or a radio source (e.g. Marx, Dickey & Mebold 1997) exists and in addition sources which have been classified as spectrally *[hard]* by HP99 and according to our analysis are consistent with AGN. We made use of archival *ROSAT PSPC* observations. In Fig. 1 we show a *ROSAT PSPC* image made from our observations of the LMC field and we give the areas where AGN have been analysed by X-ray spectral fitting. We fitted the AGN spectra with absorbed powerlaw spectral models. For the absorption we used a galactic ($N_{\rm H\,I}^{\rm gal}$) and a LMC ($N_{\rm H}^{\rm LMC}$) component. We used for $N_{\rm H\,I}^{\rm gal}$ values derived from a 21-cm *Parkes* survey of the LMC field (Brüns et al. 2001). $N_{\rm H}^{\rm LMC}$ has been determined assuming a reduced metallicity (–0.3 dex) for the LMC gas. We derive for the X-ray brightest and optically identified AGN powerlaw photon indices which are consistent with AGN type spectral indices (cf. Brinkmann et al. 2000). We also fitted absorbed powerlaw spectra to the other background sources. The uncertainties for the absorbing column densities derived for most of these sources are considerable and in order to tighten the $N_{\rm H}$ constraints for the LMC gas we made the assumption that all background sources have AGN type spectra with $-\Gamma = (2.0 - 2.5)$. We constrained $N_{\rm H}^{\rm LMC}$ for 26 background sources and derive LMC gas columns in the range 10^{20} to $(1-2)\times10^{22}$ cm^{-2}. The derived LMC absorbing column densities are given in Fig. 2 and in Tab. 1 for 21 and 10 AGN respectively.

Name RX J	$N_{\rm H}^{\rm LMC}$	$N_{\rm H\,I}$ (10^{21} cm^{-2})	$N_{\rm H_2}$	$f \pm \Delta f$ (%)
0454.1-6643	$2.5\pm^{1.5}_{1.0}$	1.4±0.1	0.39±0.54	36±32
0509.2-6954	$0.6\pm^{1.0}_{0.4}$	0.6±0.1	0.00±0.07	0 ± 25^{a}
0523.2-7015	0.2 –2.0	0.66±0.07	0.16±0.32	32±41
0524.0-7011	$0.6\pm^{0.32}_{0.20}$	0.7±0.1	-0.04±0.12	-11±41
0528.8-6539	$0.2\pm^{0.6}_{0.2}$	0.53±0.05	-0.12±0.22	-80±262
0532.0-6920	$0.8\pm^{2.0}_{0.5}$	1.1±0.1	0.00±0.22	0 ± 40^{a}
0536.9-6913	16 – 34	3.3±0.3	7.8±3.2	82±6
	16 – 34	37±4	-4.3±3.5	-30 ± 31^{b}
0546.0-6415	$0.12\pm^{0.10}_{0.10}$	0.12±0.01	0.00±0.04	0±60
0546.8-6851	$2.5\pm^{3.0}_{0.5}$	3.8±0.4	-0.46±1.1	-32±99
0547.0-7040	$13\pm^{7}_{7}$	3.0±0.3	3.6±2.5	71±15

Tab. 1: Total LMC absorbing column density, $N_{\rm H}^{\rm LMC}$, column density of molecular hydrogen $N_{\rm H_2}$ and molecular mass fraction f. (a) Constraint from $N_{\rm H}^{\rm LMC}$ derived from the hardness ratio analysis (cf. Paper II). (b) Using $N_{\rm H}$ determination from strongest H I absorption component (cf. Dickey et al. 1994).

For most of the AGN the $N_{\rm H}^{\rm LMC}$ values derived from the X-ray spectral fit agree, within the uncertainties, with the H I columns. For the background source RX J0536.9-6913 we infer an $N_{\rm H}^{\rm LMC}$ column substantially in excess of the H I column. As the source is located in a star forming region with large ($> 10^{21}$ cm^{-2}) H I columns, the 30 Dor complex, we consider the possibility that the additional gas is in molecular form. We estimated the amount of molecular gas $N_{\rm H_2}$ and the molecular mass fraction f for 10 AGN (cf. Tab. 1). We obtain for RX J0536.9-6913 $f = 0.82\pm0.06$. For the other background sources we determine upper limits for the molecular mass fraction f <20-80%. These are consistent with a mean molecular mass fraction of ~30% as derived for the LMC gas from CO surveys (cf. Rubio 1999). The location of RX J0536.9-6913 coincides with a region where enhanced CO emission has been measured (Cohen et al., 1988, Mizuno et al., 1999).

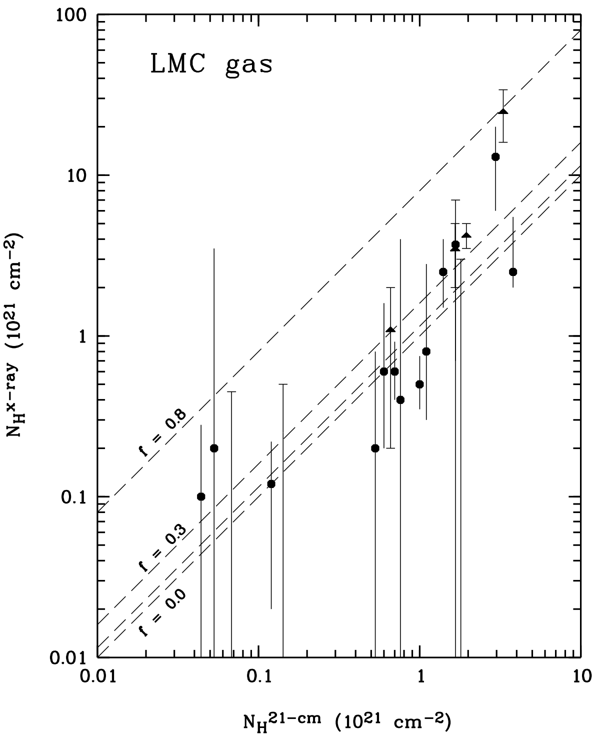

Figure 2: LMC hydrogen absorbing column density (after galactic foreground gas has been removed) as derived from the X-ray spectral fit assuming constraints on the powerlaw photon index ($-\Gamma = 2.0$–2.5). The best-fit is given as filled circle and 1σ error bars are drawn. For AGN where only an $N_{\rm H}$ range has been determined the mean value is shown as a filled triangle and 1σ error bars are drawn with small cross bars. For AGN where the lower limit for the $N_{\rm H}$ is consistent with zero the 1σ upper limit is given as a bar with a small cross bar. With dashed lines the dependences on the molecular mass fraction $f = 0,\ 0.1,\ 0.3$ and 0.8 are indicated. Figure from Paper I.

According to Cohen et al. (1988) a maximum column density due to H_2 of 2.6×10^{21} cm^{-2} is expected for the 30 Dor complex assuming an X factor of $X_{\rm LMC} = 1.7 \times 10^{21}$ cm^{-2} K^{-1} km^{-1} s. We determine for RX J0536.9-6913 a rather high column density due to molecular hydrogen of $N_{\rm H_2} = (7.8 \pm 3.2) \times 10^{21}$ cm^{-2} if we make use of the hydrogen column inferred from the 21-cm emission line measurements. This discrepancy may be explained by uncertainties in the CO intensity and the X factor, by unresolved filamentary fine structure of the H I local to the X-ray source, by local variations in the metallicity especially in star forming regions (H II regions), and by the large uncertainty inherent in the absorbing column measured from the X-ray observations. The fact that a recent *XMM-Newton EPIC pn* observation of the AGN in the 30 Dor complex (Haberl et al 2001) gives an $N_{\rm H}^{\rm LMC}$ determination which is still consistent with the column constrained from the *ROSAT PSPC* observations gives support for high absorbing columns observed in this area of the LMC. The source correlates with the radio background source 0536-692 of Dickey et al. (1994) and Marx, Dickey, & Mebold (1997) which has been well studied at 21-cm. H I in absorption which can account for the absorption observed in X-rays has been detected with *ATCA* in the direction of the radio source which coincides in position with RX J0536.9-6913. This fact may argue against molecular gas as additional absorber but may be in favor for cool dense neutral gas.

3 Intervening LMC gas columns from an $\log N - \log S$ analysis

The catalog of X-ray sources in the 10°× 10° field of the LMC as derived by HP99 contains 758 sources. Many of these sources are expected to be background AGN (or clusters of galaxies) if one takes into account the accumulative number versus luminosity distribution (the $\log N - \log S$) as e.g. given in Gilli et al. (1999) and Gilli et al. (2001). If one succeeds to identify these background X-ray sources (e.g. by applying classification schemes) in the sample of X-ray sources given in the LMC catalog then one has a tool to measure the X-ray background behind the LMC and to compare it with the X-ray background known from low absorbed fields in the sky.

We made the effort (Kahabka, 2001, hereafter Paper II) to investigate individually the sample of spectrally hard sources given in the catalog of HP99 and which are good candidate background sources. We derived the X-ray colors $HR1$ and $HR2$ for these sources and compared these colors with simulated tracks for AGN type powerlaw spectra. We selected all spectrally hard sources with more than 50 counts which are consistent with AGN (we found 53 sources) and we determined fluxes for these sources from the measured count rates. We constructed the $\log N - \log S$ relation for the sample of candidate AGN in the field of the observed LMC and we corrected the $\log N - \log S$ for incompleteness due to the variable exposure and the absorption due to the galactic and the LMC gas across the observed field. In Fig. 3 we show the resulting $\log N - \log S$. We excluded the region of extended diffuse X-ray emission in the 30 Dor complex.

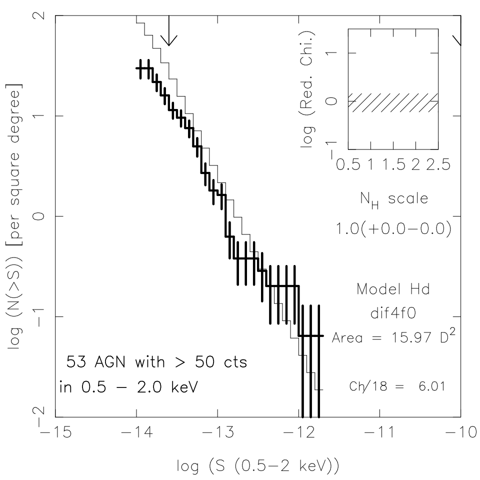

Figure 3: $\log N - \log S$ of the classified AGN sample in the LMC field excluding the extended region of hot diffuse gas around the 30 Dor complex for the spectrally hard (0.5 – 2.0 keV) band (solid histogram) and theoretical $\log N - \log S$ of the SXRB (thin histogram, Gilli et al. 1999; Gilli et al. 2001). Left panel: Corrected for the variable exposure and absorbing galactic and LMC gas (assuming $N_{\rm H} = N_{\rm H\,I}$). Right panel: Corrected for LMC gas in addition to the H I by a factor of 1.5 (for the high column regime $N_{\rm H}^{\rm LMC} > 10^{21}$ cm^{-2}).

We compared the corrected $\log N - \log S$ with the $\log N - \log S$ of the soft extragalactic X-ray background (SXRB) which has been derived from deep X-ray surveys in fields at high galactic latitudes (cf. Hasinger et al. 1998; Gilli et al. 1999; Gilli et al. 2001). We found from our observations a deficiency with respect to the standard $\log N - \log S$ of the SXRB. We consider several possibilities to explain this deficiency. (1) Systematic effects, (2) incomplete selection of the AGN sample, (3) partial blockage of the LMC by absorbing clouds, (4) gas additional to the H I gas measured with the *Parkes* beam. We cannot exclude systematic effects which may be caused by our assumptions on the photoabsorption cross sections and abundances. Also variations in the $\log N - \log S$ across the sky or a deviation of the description of the $\log N - \log S$ from the form derived from fields at a high galactic latitude cannot be excluded: The contribution of clusters of galaxies is of importance in our observed flux range (cf. Gilli et al. 1999) and may vary locally. In addition the completeness of the selection of our AGN sample may not be completely guaranteed. We also estimate the possibility that part of the LMC is covered by absorbing clouds. Assuming a fractal distribution of obscuring clouds with a projected fractal dimension of $D_{\rm p} = -1.5$ (e.g.

Stanimirovic et al. 1999) we estimate the area in the sky covered by such clouds from

$$A = -\frac{\pi}{2} D_{\rm p} \, \frac{N_{\rm large}}{(L_{\rm large})^{-D_{\rm p}}} \, (L_1^{2-D_{\rm p}} - L_2^{2-D_{\rm p}}) \tag{1}$$

Assuming there are $N_{\rm large} = 3$ large detected clouds of size $L_{\rm large} = L_2 = 660$ pc and setting a lower limit to the cloud size of $L_1 = 30$ pc we derive that an area of $3.2\square^2$ degrees of the $60\square^2$ degrees of the LMC field is covered by such clouds, i.e. 5%. This would only be a small effect and not sufficient to explain the observed deficiency in the $\log N - \log S$. The option that gas additional to the measured H I in the high column ($\geq 10^{21}$ cm^{-2}) regime of the H I alone accounts for the deficiency has also been investigated to explain the observed $\log N - \log S$. We find from the analysis in selected areas of the LMC (including the northern and southern LMC with a region north of 30 Dor as the dividing line, the supershell LMC 4, and the nebular complex N 11) that a fraction of $\sim 1.5\pm^{3.5}_{1.5}$ of gas additional to the H I measured with the *Parkes* radio telescope would account for the observed deficiency in the $\log N - \log S$ (cf. right panel in Fig. 3). We estimate that this additional $N_{\rm H}$ for the high column regime ($N_{\rm H\,I} \geq 10^{21}$ cm^{-2}) would correspond to a molecular mass fraction of $f = 0.5\pm^{0.3}_{0.5}$.

Conclusions: The value for the molecular mass fraction of LMC gas derived from X-ray spectral fitting of individual background AGN in the LMC field and from the $\log N - \log S$ analysis of an extended candidate AGN sample is very uncertain but it is consistent with that derived from CO studies in the literature.

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