The interstellar medium in Andromeda’s dwarf spheroidal galaxies: II. Multi-phase gas content and ISM conditions

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\textbf{ABSTRACT}

We make an inventory of the interstellar medium material in three low-metallicity dwarf spheroidal galaxies of the Local Group (NGC 147, NGC 185 and NGC 205). Ancillary H\textsc{i}, CO, Spitzer IRS spectra, H\textalpha and X-ray observations are combined to trace the atomic, cold and warm molecular, ionised and hot gas phases. We present new Nobeyama CO(1-0) observations and Herschel SPIRE FTS [C\textsc{i}] observations of NGC 205 to revise its molecular gas content.

We derive total gas masses of $M_g = 1.9 - 5.5 \times 10^5 M_\odot$ for NGC 185 and $M_g = 8.6 - 25.0 \times 10^5 M_\odot$ for NGC 205. Non-detections combine to an upper limit on the gas mass of $M_g \leq 0.3 - 2.2 \times 10^5 M_\odot$ for NGC 147. The observed gas reservoirs are significantly lower compared to the expected gas masses based on a simple closed-box model that accounts for the gas mass returned by planetary nebulae and supernovae. The gas-to-dust mass ratios GDR\textsuperscript{\textsc{\textsc{l}}}$\sim 37 - 107$ and GDR\textsuperscript{\textsc{\textsc{l}}}$\sim 48 - 139$ are also considerably lower compared to the expected GDR\textsuperscript{\textsc{\textsc{l}}}$\sim 370$ and GDR\textsuperscript{\textsc{\textsc{l}}}$\sim 520$ for the low metal abundances in NGC 185 (0.36 \textsc{\textsc{\textsc{Z}}}_\odot) and NGC 205 (0.25 \textsc{\textsc{\textsc{Z}}}_\odot), respectively.

To simultaneously account for the gas deficiency and low gas-to-dust ratios, we require an efficient removal of a large gas fraction and a longer dust survival time ($\sim 1.6$ Gyr). We believe that efficient galactic winds (combined with heating of gas to sufficiently high temperatures in order for it to escape from the galaxy) and/or environmental interactions with neighbouring galaxies are responsible for the gas removal from NGC 147, NGC 185 and NGC 205.

\textbf{Key words:} ISM: evolution – galaxies: dwarf – galaxies: individual: NGC 147, NGC 185, NGC 205 – Local Group – infrared: ISM

1 INTRODUCTION

Dwarf spheroidal galaxies (dSph) dominate the overall galaxy population in the Universe at the low mass end.
With most dwarf spheroidals residing in groups and clusters of galaxies, environmental effects are thought to play an important role in the formation and evolution of the dSph galaxy population. Studying the properties of the interstellar medium in dwarf spheroidal galaxies, in combination with their star formation histories, can give us clues to their formation processes (e.g., Tolstoy et al. 2009) and the role of environmental processes in their evolution (e.g., Boselli et al. 2008). Being the most prominent dSph residents of the Local Group, the three dwarf satellites of Andromeda, NGC 147, NGC 185 and NGC 205, offer the best opportunity to study the interstellar medium of dwarf spheroidal galaxies in the nearby Universe.

In De Looze et al. (2016a), we focused on the dust reservoirs in the three dSph satellites of Andromeda and show that the observed dust masses in NGC 185 and NGC 205 are significantly higher compared to the estimated metal enrichment from evolved stars and supernova remnants. Although uncertainties on the dust yields from asymptotic giant branch (AGB) and supernovae might affect the estimated dust production rates, the observed dust masses exceed predictions by an order of magnitude and can only be explained by efficient interstellar grain growth or longer dust survival times (3-6 Gyr).

Based on observational constraints of the evolved stellar populations, the dSph satellites NGC 147, NGC 185 and NGC 205 are shown to be characterised by significantly lower gas masses compared to the predicted material returned by evolved stars and the left-over gas reservoir that remains after previous star-formation episodes (Sage et al. 1998; Welch et al. 1996; De Looze et al. 2012). The gas deficiency in NGC 205 was attributed to environmental interactions with parent galaxy Andromeda and/or efficient stellar feedback (De Looze et al. 2012). To rule out that an important gaseous ISM reservoir has been overlooked in previous studies, we require an accurate quantification of the interstellar material (its mass and properties) in dSphs in combination with models that account for the gas mass returned by the evolved stellar population and supernovae. In this paper, we make a revised inventory and updated analysis of the gaseous reservoir in the three dSph satellite galaxies of Andromeda by taking into account all significant phases of their ISM. We present a new Nobeyama CO(1-0) map of the southern regions in NGC 205, Herschel PACS line spectroscopy observations for NGC 185 and Herschel SPIRE FTS spectroscopy observations for NGC 205. We furthermore use ancillary data of other gaseous components tracing the atomic gas (H I), cold (CO), CO-dark ([C ii]) and warm molecular gas (H2 rotational lines), ionised gas (Hα), and hot X-ray emitting gas.

The description of the star formation histories and characterisation of the most recent star formation rates and metal abundances for the three galaxies under study have been outlined in the three paragraphs below. Table 1 presents an overview of the general properties and available observational constraints for each of the galaxies. In Section 2, we present the new NRO 45m CO(1-0) observations, Herschel PACS and SPIRE spectroscopy data, and the ancillary datasets used to analyse the gaseous reservoirs in NGC 147, NGC 185 and NGC 205. To learn more about the physical gas conditions, we analyse the origin of the [C ii] emission in NGC 185 (3.1), quantify the photoelectric efficiency (3.2), and compare the emission of gas tracers to photo-dissociation models (3.3). Several observations are combined to derive the total gas content in the three dwarf spheroidal galaxies (Section 4). Section 5 investigates the position of dSphs on the local Kennicutt-Schmidt relation. Combining dust and gas mass reservoirs, we derive gas-to-dust mass ratios for NGC 185 and NGC 205 in Section 6. The ISM mass budget in the three dwarf spheroidal companions of Andromeda (NGC 147, NGC 185, NGC 205) is compared to a simple closed box model and discussed in light of galaxy evolution processes in Section 7. The main results are summarised in Section 8. Throughout this paper, we adopt distances of 675±27 kpc, 616±26 kpc and 824±27 kpc to NGC 147, NGC 185, and NGC 205 (McConnachie et al. 2005), respectively.

1.1 Star formation history

Dwarf spheroidal galaxies are considered to form their stars in a limited number of star formation episodes lasting a few Gyr and clearly separated by quiescent periods (e.g., Lanzafame & Matteucci 2004). Martins et al. (2012) determined that the star formation in NGC 185 has taken place in three major episodes separated by quiescent periods without any significant star formation activity. The first SF episode, during which most of the stellar content was produced, took place ~10 Gyr ago in NGC 185 (Geha et al. 2015), resulting in a stellar population with an iron abundance of [Fe/H] ~ -1.0. After the first star formation episode, which lasted a few Gyr, NGC 185 had a long quiescent period without any significant star formation activity. The presence of an intermediate age population (2-3 Gyr old) suggested a secondary star formation episode. This second cycle of star formation was considered to be the result of the build-up of mass loss from evolved stars and/or planetary nebulae (Welch et al. 1996; Davidge 2005). A similar old and intermediate stellar population has been observed in NGC 147. The old stellar population in NGC 147 has a mean age (7.5 Gyr) and metallicity ([Fe/H] ~ -0.7), making the stars considerably younger in this galaxy and more metal-rich compared to the stars in NGC 185 (with mean age of 10 Gyr and [Fe/H] ~ -1.0). This suggests that the bulk of stars in NGC 185 already formed at an earlier epoch (Geha et al. 2015). In the central regions of NGC 185, a more recent star formation episode took place that started a few 100 Myr ago. NGC 147 shows no signs of any recent star formation activity (Han et al. 1997). An old stellar population (10 Gyr, Bica et al. 1990) also dominates the overall stellar content of NGC 205, while a plume of bright blue star clusters in the central region of this galaxy was already identified 60 years ago (Baade 1951; Hodge 1973).

1.2 Star formation rates

In NGC 147, no significant star formation activity has taken place during the last 1 Gyr (Han et al. 1997). The star formation rate (SFR ~ 6.6×10^-4 M⊙ yr^-1) in the central regions of NGC 185 (inner 118") over the last ~1 Gyr has been determined from color-magnitude diagrams by Martinez-Delgado et al. (1999). The total SFR ~ 82 × 10^-4 M⊙ yr^-1 (over the entire lifetime of the galaxy) in those central re-
gions is significantly higher and consistent with a star formation history where most of the stars have been formed in the first few Gyr after the formation of the galaxy (Martínez-Delgado et al. 1999). The latter central SFR should also be considered as an upper limit given that the inner regions are affected by crowding and every blue object has been assumed to be an individual star. In a similar way, the SFR are affected by crowding and every blue object has been considered as an upper limit given that the inner regions Delgado et al. (1999). The latter central SFR should also be estimated by averaging the oxygen abundance derived for 5 central PNe reported by Richer & McCall (2008), resulting in 12+log(O/H) ~ 8.25 or Z ~ 0.36 Z⊙ (assuming a solar oxygen abundance of 12+log(O/H) ~ 8.69, Asplund et al. 2009). Similarly, Gonçalves et al. (2012) find a mean oxygen abundance of 12+log(O/H) ~ 8.20 or Z ~ 0.32 Z⊙ for NGC 185 based on independent observations for four of the same planetary nebulae. In the same way, we derive the mean oxygen abundance 12+log(O/H) ~ 8.08 (or 0.25 Z⊙) based on fourteen planetary nebulae in NGC 205 (Gonçalves et al. 2014).

We caution that the abundances of planetary nebulae (probing the evolutionary products of the intermediate mass stars) might be lower with respect to the abundances in H II regions (which probe the initial phases of massive stellar evolution) due to their different stages of evolution. Based on comparison studies of elemental abundances derived for H II regions and PNe in NGC 300 (Stasińska et al. 2013) and M 33 (Bresolin et al. 2010; Magrini et al. 2010), we consider a maximum offset of 0.15 dex between the abundances from H II regions and PNe.

2 DATA

2.1 PACS spectroscopy data of NGC 185

With the PACS spectrometer on board Herschel (Pilbratt et al. 2010), we observed 3 × 3 raster maps of the fine-structure [C II] 158 μm line in a chop-nod observing mode with 2 repetitions, which covers the central 100′′ × 100′′ area in

1 The latter mean oxygen abundance is a bit higher compared to the mean value (12+log(O/H) ~ 7.80) used in De Looze et al. (2012) which was calculated as the average of thirteen planetary nebulae analysed by Richer & McCall (2008).

2 Spaxels are spatial pixels that each contain a whole spectrum for a pixel on the sky. For the PACS spectrometer, spaxels have a size of 9.4′′×9.4′′.
the 11-12% absolute calibration uncertainty (at 63 µm and 158 µm, respectively) and the 10% relative uncertainty due to spaxel variations. [C ii] emission is clearly detected from the centre of NGC 185 (see Fig. 2, bottom left), while a more diffuse component appears to extend towards the east of the galaxy following the distribution of diffuse H i and dust clouds (see Fig. 2, top panels). The peak of [C ii] is located adjacent to the most massive dust and molecular gas clouds, and coincides with the position of young stars emerging from star forming regions (see Fig. 2, bottom left). This suggests that the majority of [C ii] emission arises from photo-dissociation regions positioned in between the star-forming regions and molecular gas reservoirs. The [O i] line is only detected in the very central region of NGC 185 (see Fig. 2, bottom right), coinciding with the peak in [C ii] emission, and near the location of several young stars. Figure 3 shows the [C ii] 158 µm (top) and [O i] 63 µm (bottom) line profiles detected in the central spaxels of the PACS spectrometer.

2.2 NRO 45m CO(1-0) observations of NGC 205

We observed the CO(1-0) line transition with the Nobeyama Radio Observatory (NRO) 45m telescope mapping the central and southern regions of NGC 205 (see Fig. 4). We mapped a 3.2′ × 2.7′ region with the On-The-Fly (OTF) mapping mode (Sawada et al. 2008) with a separation between scans of 5′. The observations were conducted during two separate runs in 2012, extending from January 22nd until January 28th and April 16th until April 25th. During both observing runs, the source IRC+30021 was used for pointing. The average wind speed during both observing runs was less than 5 m s$^{-1}$ on average. The pointing was checked every hour, on average, and found to be accurate within 5′. The full-width at half-maximum (FWHM) of the NRO 45m beam at the CO(1-0) rest frequency of 115 GHz is 16′ (which corresponds to about 64 pc at the distance of NGC 205).

We observed the CO(1-0) line with the two sideband-separating (2SB) receivers (T100H and T100V) as front-end receivers (Nakajima et al. 2008). The analog signal from T100 was converted to 4-8 GHz before being transferred to the digital FX-type spectrometer SAM45 (Spectral Analysis Machine for the 45m telescope). The back-end SAM45 was used with a frequency resolution of 488.24 kHz which was rebinned to a spectral resolution of 1 MHz or 2.6 km s$^{-1}$. The typical system noise temperature during the observations ranged between $T_{\text{sys}} \sim 200$ K and 300 K, depending on the weather conditions. The total observing time during the different observing runs was 39 hours, with a total on-source time of 20 hours.

Data reduction was done with NOSTAR, which is a reduction tool for OTF observations developed by NRO. First of all, the data with pointing errors greater than 5′ were flagged and not used for the construction of the final map. Secondly, the image rejection ratio and the main beam efficiency were used to determine the absolute flux calibration following the method by Kerr et al. (2001). The uncertainty on the flux calibration is less than 15%, which is based on the combined uncertainty from the measurement of the main beam efficiency and the daily variation of the image rejection ratio (~5% during both observing runs). The antenna temperature ($T_A$) was converted to a main beam temperature ($T_{\text{mb}}$) using a main beam efficiency of $\eta_{\text{mb}} = 0.30-0.33$ and $T_{\text{mb}} = T_A/\eta_{\text{mb}}$. The final data cube with a grid spacing of 7.5″ was created by convolving with a Gaussian-tapered Bessel function:

$$J_1(r/a) \times \frac{\exp \left(-\left(\frac{r}{b}\right)^2\right)}{r/a} \cdot \text{with } a = 1.55/\pi \text{ and } b = 2.52,$$

$$J_1(r/a) \times \frac{\exp \left(-\left(\frac{r}{b}\right)^2\right)}{r/a}$$

(1)

with $J_1$, the first order Bessel function and, $r$, the distance between the data and grid point in a pixel. After convolution, the maps have an effective angular resolution of 19.3″ (or 77 pc at the distance of NGC 205). Across our map, the average rms sensitivity ranged between $T_{\text{rms}} \sim 15$ mK and 20 mK at a velocity resolution of 2.6 km s$^{-1}$.

We detect CO(1-0) line emission in three different positions. The line detections in Positions 1 and 2A and 2B are shown in Figure 5. The line emission detected in Positions 2A and 2B is separated by only ~15″ (similar to the size of the NRO 45m beam at 115 GHz) and with peak velocities that are only 15 km s$^{-1}$ apart, we can not rule out that the two detections originate from the same cloud complex. We average the spectra of adjacent pixels with CO(1-0) detections to derive an average main beam temperature. We fit the baseline of the averaged spectra with a first order polynomial, while the line emission is fit with a Gaussian

3 http://herschel.esac.esa.int/twiki/pub/Public/PacsCalibrationWeb/-0.33±0.03 and 0.30±0.02 for the T100H and T100V receivers, respectively.

4 At the time of the observations, the main beam efficiency was

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Figure 2. Top panels: Herschel PACS 160 μm maps of NGC 185 with the positions of the blue stars (or star clusters) identified by Baade (1951) (green crosses) and clumps in the H I distribution (cyan squares) overlaid in the left panel. In the right panel, the contours of H I, CO and [C II] observations are overlaid as blue dashed, yellow and green solid lines, respectively, at their original resolution. The beam sizes of the CO (FWHM∼5″), [C II] (FWHM∼11.5″) and H I (FWHM∼28″) are indicated in the bottom right corner. The latter figures were taken from De Looze et al. (2016a). Bottom panels: Herschel PACS [C II] (left) and [O I] (right) maps of NGC 185. Beamsizes are indicated in the lower right corner of the respective images. The green contours indicate the 3, 5, 10 and 15σ S/N levels for [C II], and the 3, 5 and 8σ S/N levels for [O I]. The positions of supernova remnant SNR-1 and the centre of NGC 185 are indicated with a red diamond and black cross, respectively. All images have the same field of view (FOV).

Table 5 gives an overview of the equatorial coordinates, central velocity $V$, line width $FWHM$, average main beam temperature $T_{mb}$ and integrated line intensity $I_{CO}$ of the three positions.

The detected CO(1-0) emission at Position 1 is located near the IRAM CO(1-0) detection (with a ∼3σ significance) reported by Young & Lo (1996) at a position (RA, DEC) = (0°40′25.9″, +41°40′19″). While the central velocity (-218.8 ± 1.8 km s$^{-1}$) reported by Young & Lo (1996) is in fair agreement with our NRO 45m CO(1-0) observations (-216.1±0.6), we find a smaller line width (4.5 ± 1.1 km s$^{-1}$) compared to the values reported by Young & Lo (1996) (FWHM=19.8±3.7 km s$^{-1}$). This difference between both CO(1-0) observations can likely be attributed to the IRAM 30m beam (FWHM ~ 21″) being offset by about 7″ from the peak CO(1-0) line emission, which might not have picked up the peak of line emission. The central velocity (-215 km s$^{-1}$) and line width (~10 km s$^{-1}$) observed for H I clouds at the same position are in good agreement with the NRO 45m CO(1-0) observations. Also the line width (6.6±0.7 km s$^{-1}$)
Flux density [Jy]

− at Position 1 and is centred around a heliocentric velocity of NGC 205 is more consistent with the line width measures of NGC 205 is more consistent with the line width measures of NGC 205 of the instrument (i.e., 240 km s\(^{-1}\) to the data assuming a line width similar to the spectral resolution

The CO(1-0) emission detected at Position 2A has an FWHM of 239.52 km s\(^{-1}\) and FWHM\(_{\text{th}}\) = 239.52 km s\(^{-1}\). The red and green circles indicate the CO(1-0) pointings from Welch et al. (1998) and Young & Lo (1996), respectively. The orange circle corresponds to the FWHM (18\(^{\circ}\)) of the observed position with the JCMT at 1.1 mm (Fich & Hodge 1991). The black box indicates the region covered by our NRO 45m observations. The white triangles indicate Position 1 (top) and Positions 2A and 2B (bottom) where CO(1-0) line emission is detected from our new NRO 45m data. This Figure was taken from De Looze et al. (2012), and updated to include our recent CO observations.

Figure 4. SPIRE 250 \(\mu\)m image of NGC 205 overlaid with H\(^\text{i}\) column density contours (Young & Lo 1997, white solid lines) ranging from \(2.6 \times 10^{20}\) cm\(^{-2}\) to \(1.9 \times 10^{21}\) cm\(^{-2}\), H\(_2\) column density contours (De Looze et al. 2012, black solid lines) ranging from \(2.6 \times 10^{20}\) cm\(^{-2}\) to \(1.9 \times 10^{21}\) cm\(^{-2}\) in steps of 3.3 \(\times 10^{20}\) cm\(^{-2}\). The red and green circles indicate the CO(1-0) detection at Position 2B is centred around a heliocentric velocity of -275.5 km s\(^{-1}\), with a line width (2.5\(\pm\)0.6 km s\(^{-1}\)) that is similar to our spectral resolution. The adjacent CO(1-0) detection at Position 2B is centred around a heliocentric velocity of -290.8 km s\(^{-1}\) and has a similar narrow line width of 2.4\(\pm\)0.9 km s\(^{-1}\). The central velocities of these CO clouds are at the limit of the stellar velocities (ranging between -280 and -140 km s\(^{-1}\), Geha et al. 2010), and outside of the H\(^\text{i}\) velocity range (-260 to -140 km s\(^{-1}\)) for NGC 205 (Young & Lo 1997). We note that the central velocity of the cloud is far from the range of H\(^\text{i}\) velocities detected in our Galaxy (-130 to 45 km s\(^{-1}\), Braun et al. 2009) and this emission does not belong to our Galaxy. The disturbed nature of the distribution of atomic and molecular clouds in NGC 205 (Young & Lo 1997) and the offset from the main stellar body in NGC 205, suggests that the gas clouds have not yet settled into a stable configuration. The irregular disposition of this molecular gas cloud might be the result of a recent tidal interaction which has disturbed the gas distribution in NGC 205. Alternatively, the CO(1-0) line emission at Position 2B might be a false detection and rather correspond to a noise peak, given the small line width which resembles the spectral resolution of the observations. The line emission detected in Position 2A is unlikely to correspond to instrumental noise given its detection in several adjacent pixels (corresponding to 1.5\(\times\)FWHM), although we can not entirely rule out that it corresponds to a local noise peak.

The line emission in our NRO 45m map of NGC 205 is detected in only 2 to 7 adjacent 7.5\('\)×7.5\('\) sized pixels, indicating that the size of molecular clouds in NGC 205 is extremely small with typical values of \(\lesssim 20-25\)\('\) (or 80-100 pc). Interferometric CO(1-0) observations with the BIMA array (with a 40 pc × 20 pc beam) can barely resolve molecular clouds and measure a cloud size around 40-60 pc for a giant molecular cloud (GMC) in the north of NGC 205 (Young & Lo 1996). Based on a cloud size of 40-60 pc, the first Larson scaling relation between a cloud’s size and velocity dispersion (Larson 1981) predicts a line width of 4.5-5.2 km s\(^{-1}\). The similarity with the observed line widths (2.5-4.4 km s\(^{-1}\)) suggests that the clouds are virialised and experience very little internal gas turbulence.

\(\sigma\)} of the CO emission detected with IRAM in the north of NGC 205 is more consistent with the line width measurement from our NRO 45m observations.

The CO(1-0) emission detected at Position 2A has an average line intensity similar to the line emission detected at Position 1 and is centred around a heliocentric velocity of -275.5 km s\(^{-1}\), with a line width (2.5\(\pm\)0.6 km s\(^{-1}\)) that is similar to our spectral resolution. The adjacent CO(1-0) detection at Position 2B is centred around a heliocentric velocity of -290.8 km s\(^{-1}\) and has a similar narrow line width of 2.4\(\pm\)0.9 km s\(^{-1}\). The central velocities of these CO clouds are at the limit of the stellar velocities (ranging between -280 and -140 km s\(^{-1}\), Geha et al. 2010), and outside of the H\(^\text{i}\) velocity range (-260 to -140 km s\(^{-1}\)) for NGC 205 (Young & Lo 1997). We note that the central velocity of the cloud is far from the range of H\(^\text{i}\) velocities detected in our Galaxy (-130 to 45 km s\(^{-1}\), Braun et al. 2009) and this emission does not belong to our Galaxy. The disturbed nature of the distribution of atomic and molecular clouds in NGC 205 (Young & Lo 1997) and the offset from the main stellar body in NGC 205, suggests that the gas clouds have

\(\sigma\)}
We derive molecular gas masses \( M_{\text{H}_2} = A \, N_{\text{H}_2} \, m_{\text{H}_2} \) where, \( A \) is the surface of the CO-emitting region (cf. the number of detected pixels in every position indicated in Table 2), \( N_{\text{H}_2} \), is the molecular hydrogen mass and the column density of \( \text{H}_2 \) is calculated as:

\[
N_{\text{H}_2} = X_{\text{CO}} I_{\text{CO}(1-0)}
\]

with, \( I_{\text{CO}(1-0)} \), the integrated main beam line intensity in units of K km s\(^{-1}\) and, \( X_{\text{CO}} \), the conversion factor. Since the \( X_{\text{CO}} \) scaling factor might depend on metallicity, we apply the usual Galactic scaling factor \( (X_{\text{CO}}=2.0 \times 10^{20} \text{cm}^{-2} \text{[K km s}^{-1}])^{-1}; \) Strong & Mattox 1996; Dame et al. 2001; Ackermann et al. 2011) as well as a \( H \)-band luminosity-dependent conversion factor \( (X_{\text{CO}}=12.5 \times 10^{20} \text{cm}^{-2} \text{[K km s}^{-1}])^{-1} \) following the prescriptions from Boselli et al. (2002). The \( H \)-band luminosity of a galaxy is shown to scale with the abundance of metals, and can be considered as a metallicity-dependent \( X_{\text{CO}} \) factor. We derive molecular gas masses of \( M_{\text{H}_2}=1.0-6.2 \times 10^4 \, M_\odot, \, 0.8-5.0 \times 10^4 \, M_\odot \) and \( 0.2-1.3 \times 10^4 \, M_\odot \) for Positions 1, 2A and 2B, respectively, within the limits of the two different conversion factors. A comparison with previous CO(1-0) observations of the north and central regions of NGC 205 (see Section 4.1) show that the molecular gas clouds in the south account for only one tenth of the total molecular gas reservoir in NGC 205.

Total molecular gas masses (see Table 3) using a metallicity-dependent \( X_{\text{CO}} \) factor are more than three times higher compared to the atomic gas mass in NGC 205 \( (M_{\text{H}_1}=4 \times 10^4 \, M_\odot) \), which seems unrealistic given the low star formation activity in NGC 205. The choice of a Galactic \( X_{\text{CO}} \) factor is also consistent with the Galactic conversion factor derived by Bolatto et al. (2008) for a molecular cloud in the centre of NGC 205 based on virial mass assumptions. Molecular gas mass depletion factors (log \( \tau_{\text{depl}} \sim 0.6-0.8 \, \text{Gyr} \)) based on \( H \)-band luminosity-dependent \( X_{\text{CO}} \) factors would however better agree with the trend between molecular gas depletion time scale and specific star formation rate \( (\text{sSFR} = \text{SFR}/M_\odot) \) observed for the COLD GASS sample (Saintonge et al. 2011). To account for uncertainties on the \( X_{\text{CO}} \) factor, we will mention molecular gas masses derived from both Galactic and \( H \)-band luminosity-dependent \( X_{\text{CO}} \) factors in the remainder of this work.

### 2.3 SPIRE FTS spectroscopy data of NGC 205

Herschel observations of NGC 205 were acquired as part of the Guaranteed Time (GT) program “Very Nearby Galaxies Survey (VNGS)” (PI: C. Wilson). The SPIRE FTS spectra were obtained in sparse spatial sampling and high spectral resolution mode, covering the 194-671 \( \mu \text{m} \) wavelength range. One single pointing targeting the CO peak in the North of NGC 205 (see Fig. 6) was observed with 74 repetitions. The 35 detectors of the SSW (SPIRE Short Wavelength) array covered the 194-313 \( \mu \text{m} \) range, while the SLW (SPIRE Long Wavelength) array of 19 detectors covered the 303-671 \( \mu \text{m} \) wavelength range. The SSW and SLW arrays have an average FWHM of 19” and 34”, respectively (Makiwa et al. 2013).

The SPIRE FTS data were reduced in HIPE v14.0.0, with version SPIRE_CAL_14_2 of the calibration files. The standard pipeline in HIPE for single pointing SPIRE spectrometer observations was used for data reduction, assuming a point source calibration without apodisation. The standard pipeline included a first and second order deglitching procedure, non-linearity and phase corrections, baseline subtraction, and corrections for the telescope and instrument emission. We fit spectral lines in the SPIRE FTS data using the SPIRE Spectrometer Line Fitting algorithm in HIPE. All emission lines of interest (i.e., CO line transitions from \( ^{12}\text{CO}(4-3) \) up to \( ^{12}\text{CO}(13-12) \) and the two \([\text{C} \, \text{ii}] \) line and \([\text{N} \, \text{ii}] \) 205 \( \mu \text{m} \) line transitions) were fit simultaneously using a third order polynomial for the continuum while the line profile is fit with a sinc function. We assume the line pro-

![Figure 5. The CO(1-0) line profiles at the three positions (showing the average emission in a single pixel) where CO(1-0) line emission was detected in our NRO 45m map covering the southern part of the galaxy NGC 205.](image-url)
Similarly constrain or 65 Jy km s\(^{-1}\); towards longer wavelengths). Based on the typical line widths (\(\lesssim 20\) km s\(^{-1}\), Young & Lo 1996, 1997) for the observed H\(_{\text{I}}\) and CO line transitions in NGC 205, we are confident that the line profiles will be set by the instrument’s spectral imprint.

We do not detect CO, [C \(_{\text{II}}\)], or [N \(_{\text{II}}\)] emission in any of the SPIRE FTS bolometers. The 1\(\sigma\) upper limits derived from the line fitting algorithm for the spectra of the SPIRE SLW-C3 bolometer constrain the [C \(_{\text{II}}\)] integrated line fluxes in the CO-peak in the North (\(I_{[\text{C}\,\text{II}]\,1-0} \lesssim 1.06 \times 10^{-18}\) W m\(^{-2}\) or 65 Jy km s\(^{-1}\); \(I_{[\text{C}\,\text{II}]\,2-1} \lesssim 1.09 \times 10^{-18}\) W m\(^{-2}\) or 40 Jy km s\(^{-1}\)) and the spectra of the SPIRE SLW-D2 bolometer similarly constrain [C \(_{\text{II}}\)] integrated line fluxes in the centre of NGC 205 (\(I_{[\text{C}\,\text{II}]\,1-0} \lesssim 1.04 \times 10^{-18}\) W m\(^{-2}\) or 63 Jy km s\(^{-1}\); \(I_{[\text{C}\,\text{II}]\,2-1} \lesssim 1.07 \times 10^{-18}\) W m\(^{-2}\) or 40 Jy km s\(^{-1}\)). We furthermore use the 1\(\sigma\) upper limits on the [N \(_{\text{II}}\)] 205\(\mu\)m flux (\(I_{[\text{N}\,\text{II}]\,1-0} \lesssim 8.08 \times 10^{-19}\) W m\(^{-2}\)) in the centre of NGC 205 to constrain the [C \(_{\text{II}}\)] contribution from ionised gas in Section 3.1.

### 2.4 Ancillary data

For NGC 147, we only have H\(_{\text{I}}\) and CO observations to constrain the gas mass. We rely on the upper gas mass limits from H\(_{\text{I}}\) and H\(_{\text{2}}\) observations reported by Young & Lo (1997) and Sage et al. (1998), respectively, to constrain the gas content in NGC 147.

For NGC185, we have H\(_{\text{I}}\), CO and H\(_{\text{2}}\) observations and Spitzer Infrared Spectrograph (IRS) spectra with rotational H\(_{\text{2}}\) lines to constrain the atomic, cold molecular, ionised and warm molecular gas masses. We reduced H\(_{\text{I}}\) data for NGC 185 observed with the Very Large Array (VLA) in configurations C (8 hr) and D (4.5 hr), in a similar way as presented in Young & Lo (1997). We derive a moment-0 map of the H\(_{\text{I}}\) observations following the same strategy as Young & Lo (1997). The H\(_{\text{I}}\) map was derived at medium resolution of 28\(^{\prime}\) \times 26\(^{\prime}\) \((or 84\) pc \times 78\) pc) with rms noise level of 0.54 mJy beam\(^{-1}\) (0.46 K), which corresponds to a H\(_{\text{I}}\) column density of \(\sim 3 \times 10^{19}\) cm\(^{-2}\). At the medium resolution of 28\(^{\prime}\) \times 26\(^{\prime}\), we observe a peak in H\(_{\text{I}}\) column density \(N_{\text{HI}} \sim 3.1 \times 10^{20}\) cm\(^{-2}\). Assuming optically thin H\(_{\text{I}}\) emission, we derive a total H\(_{\text{I}}\) mass of \(M_{\text{HI}} = 1.1 \times 10^{5}\) M\(_{\odot}\), scaled to our adopted distance \(D = 0.616\) Mpc. We, furthermore, use the CO map obtained from interferometric observations with the Berkeley-Illinois-Maryland Association (BIMA) array presented by Young (2001). For the analysis in this paper, we use the CO intensity map with 5.5\(^{\prime}\) \times 4.6\(^{\prime}\) (17 pc \times 14 pc) resolution and a rms noise level of 0.070 Jy beam\(^{-1}\) (or 0.25 K).

For NGC 205, we have H\(_{\text{I}}\), CO and H\(_{\text{2}}\) observations to constrain the atomic, cold molecular and ionised gas masses. The CO observations in the north and centre of NGC 205 (Young & Lo 1996; Welch et al. 1998) are complemented with our new NRO 45m observations covering the southern regions of NGC 205 (see Section 2.2). We furthermore have Herschel SPIRE FTS spectra with [C \(_{\text{II}}\)] line transitions that allow us to constrain the CO-dark molecular gas content in NGC 205. The ancillary H\(_{\text{I}}\) and JCMT CO(3-2) data sets used for NGC 205 were described in De Looze et al. (2012).
3 PHYSICAL GAS CHARACTERISTICS

3.1 Origin of the [C II] emission

With an ionisation potential of 11.3 eV, the [C II] line emission in NGC 185 can originate from photo-dissociation regions (PDRs), the cold neutral medium (CNM), and ionised gas phases. The [C II] contribution of the ionised gas phase is considered to be negligible in NGC 185 given the weak emission of ionised gas tracers (e.g., Hα) and the absence of a strong radiation field (De Looze et al. 2016a). The latter argument is also supported by the negligible [C II] contribution from ionised gas in NGC 205 assuming that its ISM conditions are similar to NGC 185. The [C II] contribution from ionised gas is estimated in NGC 205 based on the 1σ upper limit on its [N II] 205 μm emission as observed with the SPIRE FTS instrument onboard Herschel (see Section 2.3). Theoretical models predict line ratios of [C II]/[N II] 205 ~ 3-4 for a range of different electron densities (Oberst et al. 2006).

Based on the lower limit on the observed [C II]/[N II] 205 line ratio ([C II]/[N II] 205 $\geq$ 123) in NGC 205, we estimate a maximum [C II] contribution of the ionised gas phase of ≤4%. To predict the [C II] emission produced in the cold neutral medium excited by collisions with hydrogen atoms or molecules, we apply Eq. 1 from Madden et al. (1997):

$$I_{\text{CII}} = 2.35 \times 10^{-22} N_{\text{C}^+} \left( \frac{2 \times \exp(-91.3/T)}{1 + 2 \times \exp(-91.3/T) + (n_{\text{H}_2} / n_{\text{H}})} \right)$$

with $I_{\text{CII}}$, the [C II] intensity in units of erg s$^{-1}$ cm$^{-2}$ sr$^{-1}$, and $N_{\text{C}^+}$, the $C^+$ column density calculated as $N_{\text{C}^+} = X_{\text{C}^+} N_{\text{H}}$ with $N_{\text{H}}$, the H I column density. We assume a gas temperature $T = 50$K and gas density $n_{\text{H}} = 100$ cm$^{-3}$ typical for the cold neutral medium (Madden et al. 1997). The $C^+/H$ abundance ($X_{\text{C}^+} \sim 5.0 \times 10^{-4}$) is scaled relative to the solar carbon abundance ($X_{\text{C}^+} \sim 3.0 \times 10^{-4}$; Sofia et al. 1997) based on the metallicity of NGC 185 (0.36 Z$_\odot$, see Section 1.3) under the assumption$^5$ that all of the carbon is in the form of $C^+$. We assume a critical density $n_{\text{crit}}(\text{H}) \sim 1.6 \times 10^4$ cm$^{-3}$ (Goldsmith et al. 2012) for collisions with H atoms.

We convolve the observed [C II] map to the resolution of the H I observations ($\sim 28''$) to compare the observed [C II] intensity with the predicted contribution from the cold neutral medium. We find [C II] contributions ranging from 12% to 25%, implying that only up to a quarter of the [C II] emission originates from the cold neutral medium. The highest contributions from H I clouds to the [C II] emission occur in the more diffuse emission regions, while the [C II] contribution from the cold neutral medium reaches a minimum in the dust mass peak south-west of the centre. The small contribution from H I clouds suggests that the majority of [C II] emission in NGC 185 originates from PDRs.

Based on the total integrated CO flux density reported by Young (2001) ($S_{110} \sim 8.8$ Jy km s$^{-1}$) and the sum of the $\geq 3\sigma$ regions in the [C II] map map ($F_{\text{CII}}$ (total) = $1.33 \times 10^{-18}$ W m$^{-2}$), we derive a [C II]/CO ratio of $\sim 3.9 \times 10^3$. The line ratio in NGC 185 is higher compared to the [C II]/CO ratio observed in NGC 205 ($\sim 1.9 \times 10^3$, De Looze et al. 2012), similar to the range of values observed in starburst galaxies (Stacey et al. 1991; Negishi et al. 2001), but at the low end of the line ratios observed in low-metallicity star-forming dwarf galaxies, ranging from 4,000 to 80,000 (Madden et al. 2006; Cerni et al. 2010; Madden et al. 2016). In these low-metallicity star-forming dwarf galaxies, CO molecules are more easily photo-dissociated due to the hard radiation and a porous ISM structure, leaving behind a layer of self-shielding H$_2$ that is not traced by CO observations. Based on the low [C II]/CO line ratios in dSphs, this CO-dark gas component (Wolfire et al. 2010) is expected to be significantly less important in NGC 185 and NGC 205 compared to the CO-dark gas reservoir in metal-poor star-forming dwarfs. The UV radiation fields in these dSphs is several times weaker compared to star-forming dwarf galaxies, enabling CO molecules to survive and trace the bulk of H$_2$ gas mass.

3.2 Photoelectric efficiency

A map of the total-infrared (TIR) emission in NGC 185 is calculated based on the MIPS 24 μm, PACS 100 μm and PACS 160 μm maps and the prescriptions of Galametz et al. (2013). For the computation of the TIR emission, all maps have been convolved to the resolution of the PACS 160 μm waveband with the appropriate kernels from Aniano et al. (2011). To measure line intensities, we similarly convolve all line maps to the resolution of the PACS 160 μm waveband. Since the [O I] line is only detected in the centre of NGC 185, we measure fluxes ($F_{\text{CII}} = 3.5 \pm 0.3 \times 10^{-17}$ W m$^{-2}$, $F_{\text{OII}} = 8.6 \pm 5.0 \times 10^{-18}$ W m$^{-2}$, $F_{\text{IR}} = 2.4 \pm 0.1 \times 10^{-15}$ W m$^{-2}$)$^6$ within a circular aperture of radius R=12.1'' (or similar to the FWHM of the PACS 160 μm beam) towards the centre of NGC 185. Since [O I] emission is only detected in the central spaxel, we can also measure the total [O I] flux ($F_{\text{OII}} = 10.6 \pm 0.8 \times 10^{-18}$ W m$^{-2}$) by applying a point-source correction to the flux detected in the central spaxel. Given that the uncertainty on the corrected flux measurement from the central spaxel is lower, we will use the latter [O I] flux measurement in the remainder of this work.

Based on these line measurements for the central region, we derive [C II]/TIR = 0.015±0.004 and [C II]/[O I]/TIR = 0.021±0.004 line ratios. The line ratios are indicative of the efficiency of the photoelectric effect in case the [C II] and [O I] line emission is a good proxy for the gas cooling (and thus gas heating) and TIR is representative of the energy of stars that goes into heating the dust. With ratios higher than 1%, the photoelectric heating of neutral gas in the central regions of NGC 185 is considered more efficient compared to the average [C II]/[O I] ratios (0.1-1%) in normal star-forming galaxies (e.g., Malhotra et al. 2001; Brauer et al. 2008; Smith et al. 2010). Given the soft radiation field in NGC 185 and the bright features of polycyclic aromatic hydrocarbons (PAHs) detected in the Spitzer IRS spectra (Marleau et al. 2010),

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$^5$ This assumption might not be appropriate given the soft radiation field and low gas temperature $T \sim 40-70$ K in NGC 185, which might prevent the ionisation of carbon and/or excitation of $C^+$. For lower $C^+$ abundances, the CNM contribution to the [C II] emission will be smaller than the values quoted here.

$^6$ The uncertainty on the TIR emission accounts for the observational uncertainties on the MIPS 24 μm and PACS measurements and the scatter in the calibrations of Galametz et al. (2013).
the high photo-electric efficiency might be attributed to a high PAH abundance and/or a low fraction of grain charging. Similarly high photoelectric efficiencies were observed in a sample of low surface brightness dwarf galaxies (Cigan et al. 2016).

3.3 PDR diagnostics

To examine the state of the gas in NGC 185, the observed [C ii] and [O i] line and total-infrared (TIR) emission are compared to PDR models using the PDR Toolbox (PDRT, Pound & Wolfire 2008). For a comparison of the observed [O ii]/[C ii] and ([C ii]+[O i]/TIR) line ratios to PDR models, we assume that all of the [C ii] and [O i] emission originates from PDRs. The line ratios in the PDR toolbox are calculated for a plane-parallel geometry with elemental abundances and grain properties fixed for a metallicity 1Z⊙. Due to the assumption in the PDR models of a slab geometry that is illuminated and emitting on one side, we need to make certain corrections to the observed line emission before correcting our observations as followed by Parkin et al. (2013, 2014) and Hughes et al. (2015). Since we observe the front and back side emission of clouds in NGC 185 (under the assumption of optically thin infrared emission), we divide the observed TIR emission by a factor of two to be consistent with the model that only accounts for emission from the front side of the cloud. Because the [O i] line becomes optically thick relatively fast, we multiply the observed [O i] line emission by a factor of two to account for the clouds that have their optically thick side oriented towards us.

Based on the corrected line ratios ([O i]/[C ii] = 0.61 ± 0.15 and ([C ii]+[O i])/TIR = 0.047 ± 0.009), PDR models predict a ISRF scaling factor, G0 = 31.6, and a hydrogen gas density, nH = 10^3.75 cm^-3. The PDR line diagnostics suggest a stronger radiation field (G0 = 31.6) than derived from the dust SED modelling (G0 = 1-3, De Looze et al. 2016a). It is plausible that geometry effects play an important role in the determination of the line ratios at the working resolution of a few tens of pc. With the [O i] line being detected merely in the very central 9.4′×9.4′ (or 28×28 pc^2) spaxel of the raster as opposed to the [C ii] detection which covers an area of 110 pc × 75 pc, the actual [O i]/[C ii] line ratio (accounting for the source sizes) will be lower due to the [O i] emission not filling the entire beam. Accounting for the beam filling factors would shift the PDR model parameters (G0, nH) towards lower values, compatible with the SED fitting results on spatial scales of 36″ or ∼100 pc. If we include the CO(1-0) line emission that was detected in the high-resolution BIMA CO map presented by Young (2001) in the PDR modelling (after correcting the CO(1-0) line emission by a factor of 2 to account for the optically thick CO clouds), we derive PDR model parameters of G0 = 1.0 and nH = 10^4.25 cm^-3 which are more consistent with the dust SED modelling results.

The origin of [C ii] and [O i] emission in NGC 185 might differ from the classical picture of collisional excitation in PDRs. Turbulent heating by shocks is likely to take place in NGC 185 based on the observation of shock-excited lines (e.g., H2 0-0 S0 to S(6), [N ii] 6584, [S ii] 6716,6731, [Fe ii] 26 μm; Marleau et al. 2010; Martins et al. 2012). The importance of mechanical heating due to turbulence in shocks has been shown to play an important role in PDRs (e.g., Appleton et al. 2013), even for low shock velocities (Lesaffre et al. 2013). The low warm-to-cold gas fraction in NGC 185 (see Section 4.3) however suggest that the heating through shocks is negligible compared to radiative heating processes. Considering the old nature of the SNR in NGC 185 with an estimated shock velocity ≤ 85 km s^-1 (Gonçalves et al. 2012), shock excitation might be able to account for the observed [O i] emission in NGC 185 for shock velocities ≥ 35 km s^-1. The same model could provide at most 10% of the observed [C ii] emission in NGC 185. In case a significant fraction of the [O i] 63 μm is excited by shocks, the PDR model parameters would shift to lower G0 and nH. A possible contribution of the old stellar population to the TIR emission, on the other hand, would shift the data points to higher G0 and nH values.

Based on clear detections of the optical [O i] 6300Å line (Martins et al. 2012) with a critical density n_{crit}(H) = 10^6 cm^-3 and the infrared [Fe ii] 26 μm and [Si ii] 34.8 μm lines (Marleau et al. 2010) with critical densities of n_{crit}(H) = 2×10^6 cm^-3 and n_{crit}(H) = 3×10^5 cm^-3, respectively, the presence of a denser (nH ~ 10^4−5 cm^-3) PDR region in the central regions of NGC 185 is also hinted at. We argue that the filling factor of these dense PDR regions is small compared to the rest of the gaseous ISM with the detection of the [O i] 63 μm line limited to the central spaxel and based on the small cloud sizes measured from interferometric CO observations (Young & Lo 1996). The PDR model parameters derived based on the H2 S(0), S(1) and S(2) lines also suggests the presence of gas illuminated by radiation fields G0 ≥ 3×10^7 and gas densities nH ~ 10^4 cm^-3. The detection of several tracers with high excitation temperatures hints at the presence of a gas reservoir exposed to stronger radiation fields or would require alternative excitation mechanisms (e.g., shocks).

To derive a PDR surface temperature (T ~ 40-70 K) for NGC 185, we rely on the average gas density nH ~ 10^4−5 cm^-3 and a moderate radiation field G0 ~ 1-10 derived from dust SED fitting and PDR modelling. An average PDR temperature of T~50 K is used in Section 4.2 to obtain an upper limit for the molecular gas mass traced by [C i].

4 TOTAL GAS RESERVOIR

We combine the H i, CO(1-0), ionised gas, H2 and X-ray observations to obtain total gas masses for NGC 147, NGC 185 and NGC 205. Table 3 provides an overview of the different gas mass measurements for the three galaxies.

4.1 H i and CO observations

For NGC 147, the 3σ upper H i mass limit from Young & Lo (1997) has been scaled to our adopted distance (M Hi ≤ 3.7 × 10^5 M⊙). The 1σ upper CO intensity limit (I_{CO} < 0.037 K km s^-1) reported by Sage et al. (1998) is used to derive a 3σ upper limit M_{HI} ≤ 1.3 × 10^5 M⊙ and ≤ 15.8 × 10^4 M⊙.
for a Galactic (X_{CO} = 2.0 \times 10^{20} \text{ cm}^{-2} \cdot \text{K km s}^{-1}) and H-band luminosity-dependent (X_{CO} = 24.3 \times 10^{20} \text{ cm}^{-2} \cdot \text{K km s}^{-1}) conversion factor.

For NGC 185, we adopt the H I mass reported in Young & Lo (1997), M_{HI} = 1.1 \times 10^5 M_{\odot}, scaled to our adopted distance. From the CO moment-0 map reported in Young (2001), we derive the H2 column density based on N_{H2} [cm^{-2}] = X_{CO} I_{CO(1-0)} with, I_{CO(1-0)} the 2.85 \text{ K km s}^{-1} line intensity in units of K km s^{-1}. We apply two types of conversion factors: a Galactic conversion factor (X_{CO} = 2.0 \times 10^{20} \text{ cm}^{-2} \cdot \text{K km s}^{-1}), Strong & Mattox 1996; Dame et al. 2001; Ackermann et al. 2011) and a H-band luminosity-dependent conversion factor (X_{CO}=20.8\times10^{20} \text{ cm}^{-2} \cdot \text{K km s}^{-1}), based on the two extremes, we find a molecular gas mass in the range M_{H2} = 2.8-29.1 \times 10^5 M_{\odot}. In De Loore et al. (2012), we derived a total H I mass of M_{HI} = 4.0 \times 10^5 M_{\odot} for NGC 205. The molecular gas mass (M_{H2} \sim 2.1-13.1 \times 10^5 M_{\odot}) based on CO(1-0) observations in the northern and central regions in NGC 205 (Young & Lo 1996; Welch et al. 1998) is recalculated for Galactic and H-band luminosity-dependent X_{CO} factors. We, therefore, add the molecular gas mass derived from the new detections from our NRO 45m observations (M_{H2} \sim 0.2-1.3 \times 10^5 M_{\odot}; see Section 2.2), which sums up to a total molecular gas mass of M_{H2} \sim 2.3-14.4 \times 10^5 M_{\odot}.

4.2 Cold CO-dark molecular gas

Due to the multi-phase origin of the [C I] line emission (see Section 3.1), we would require a detailed ISM model to disentangle the [C I] emission that is originating from the molecular gas phase. Since such modelling requires an extensive set of multi-phase tracers, we opt to probe the cold molecular gas mass that is not probed by CO observations based on [C I] line observations. The Herschel SPIRE FTS observations of NGC 205 allow us to derive 1σ upper limits for the undetected [C I] line transitions (see Section 2.3). Based on those 1σ upper limits for the [C I] line intensities, we derive upper limits on the molecular gas masses based on Eq. 12 in Papadopoulos et al. (2004):

\[
M_{H2} = 4.92 \times 10^{19} \nu^{-2} \left(1 + z - \sqrt{1 + z^2}\right) \left\{X_{\text{CO}} \right\}^{-1} \times
\left(\frac{A_{ul}}{10^{-7} A_{ul}^{-1}}\right)^{-1} Q_{ul}^{-1} (\text{Jy km s}^{-1})^{-1}
\]

where, \(h_0 = 100h^0 \text{ km s}^{-1} \text{ Mpc}^{-1}\) with \(h_0 = 67.8 \text{ km s}^{-1} \text{ Mpc}^{-1}\) (Planck Collaboration et al. 2016), \(z\), is the redshift, X_{CO}, is the neutral carbon abundance, A_{ul}, is the Einstein coefficient for spontaneous emission, Q_{ul}, is the excitation rate coefficient and, I_{ul}, is the [C I] line intensity. The Einstein coefficients (A_{ul}=7.93\times10^{-8} s^{-1}, A_{ul}=2.68\times10^{-7} s^{-1}, A_{ul}=2\times10^{-14} s^{-1}) are taken from Papadopoulos et al. (2004). The Q_{ul} coefficients were calculated under non-local thermal equilibrium (NLTE) conditions for an average gas density n_{H2} \sim 10^{3-4} \text{ cm}^{-3} and gas temperature T = 50 K (see Section 3.3) following the recipes from Papadopoulos et al. (2004), and result in Q_{ul}=0.52 and Q_{ul}=0.20 for n_{H2}=10^{3} \text{ cm}^{-3} and Q_{ul}=0.45 and Q_{ul}=0.31 for n_{H2}=10^{4} \text{ cm}^{-3}. The [C I]/H2 abundance ratio is observed to range between values of 10^{-5} and 10^{-4} in local and high-redshift galaxy samples (Ferking et al. 1989; Ikeda et al. 2002; Israel & Baas 2003; Weiß et al. 2005; Walter et al. 2011). Simulations show that the neutral carbon abundance mostly varies with metallicity (X_{CO} \propto Z^{-1}) and hardly depends on radiation field strength, G_{\nu} (Glover & Clark 2016). We therefore assume a conservative lower limit ([C I]/H2 \sim 10^{-7}) based on the low metallicity of the three dSphs.

Inserting those values in Eq. 4, we derive 1σ upper molecular gas mass limits of M_{H2} \leq 10^5 M_{\odot} for typical gas densities of 10^{3} and 10^{4} \text{ cm}^{-3} in the CO peak in the north of NGC 205. Similar upper molecular gas mass limits of M_{H2} \leq 10^6 M_{\odot} are derived in the centre of NGC 205. We only provide the gas masses derived from the [C I] 1-0 line transitions, since they give the tightest upper limits. These 1σ upper mass limits are smaller than the molecular gas masses estimated from PDR models. For gas densities of n_{H2} \sim 10^{3-4} \text{ cm}^{-3} and a radiation field G_{\nu} \in [1,10], the PDR models from Kaufman et al. (1999) predict line intensity ratios of [C II]/[C I] 1-0 \sim 1-10 and [C II] 2-1/[C II] 1-0 \sim 2 (see plots in the PDR toolbox, Pound & Wilfere 2008). We derive a [C I] 158 \mu m line flux of 1.4 \times 10^{-16} W m^{-2} (or 2212 Jy km s^{-1}) for NGC 205 from Herschel observations (De Loore et al. 2012). PDR models would thus predict line intensities of [C II] 1-0 \sim 221-2212 Jy km s^{-1} and [C II] 2-1 \sim 110-1106 Jy km s^{-1}. Based on the PDR model predictions, we would expect both [C I] line transitions to be detected. The non-detection of the neutral carbon line transitions in NGC 205 might reflect a difference in filling factors between the ISM phases probed by [C II] and [C I]. Studies of low-metallicity star-forming dwarf galaxies show that the filling factor of the cold dense molecular gas phase probed by [C I] is lower compared to the ISM phases probed by [C II] (De Loore et al. in prep.), which might also explain the non-detection of the [C I] lines in NGC 205. With the lowest CO transitions probing the cold and dense molecular gas, the filling factor of [C II] emitting clouds is thought to be more compatible
with the CO-emitting surfaces of dense clouds. Based on the integrated CO 1-0 line intensity (0.39 K km s\(^{-1}\)) observed in the centre of NGC 205 (Welch et al. 1998) and the theoretical line ratio of [C ii] 1-0/CO 1-0 ∼ 25 derived for a PDR model with (G\(_{\text{0}}\), n\(_{\text{0}}\)) = (1, 10\(^{18}\) cm\(^{-3}\)), we can put a limit on the line intensity I\(_{1}\) 1-0 ∼ 10\(^{-18}\) W m\(^{-2}\) in the centre of NGC 205 which is comparable to the 1σ noise level in the SPIRE FTS spectra and consistent with the non-detection of [C ii] in the smaller SPIRE FTS beam (FWHM=40′′).

Earlier works have already shown that the intensity and/or 

De Looze et al. (2012, derived for a kinetic gas temperature T=20 K typical of molecular clouds. When adopting a critical density of \(n_{\text{crit}}\) for the [C ii] line emission predicted by PDR models can be inconsistent with observations and suggest a smaller filling factor for denser clouds (e.g., Keene et al. 1985; Schirò et al. 2014).

We can furthermore derive an upper limit on the CO-dark molecular gas reservoir based on the Herschel [C ii] observations of NGC 185. If we account for the negligible [C ii] contribution from ionised gas and the estimated [C ii] emission from neutral atomic gas (see Section 3.1), we can invert Eq. 3 to derive the C\(^+\) column density, N\(_{\text{C}^+}\), in the molecular gas phase from the residual [C ii] emission after subtracting the [C ii] contribution from neutral atomic gas clouds. When adopting a critical density of \(n_{\text{crit}}\) = 7600 cm\(^{-3}\) for collisions with H\(_2\) molecules (see Goldsmith et al. 2012, derived for a kinetic gas temperature T=20 K typical of molecular clouds) and assuming the best-fitting PDR model parameters (\(n_{\text{H}}=10^{18.75}\) cm\(^{-3}\) and T=50 K, see Section 3.3), we derive a molecular gas mass of \(\sim 4\times10^4\) M\(_{\odot}\) for the [C ii] emitting gas. Assuming a lower PDR gas density (10\(^{-3}\) cm\(^{-3}\)) could increase this molecular gas mass by a factor of \(\sim 4\). The latter value should be regarded as a strict upper limit since part of the [C ii] emission might originate from neutral atomic gas clouds rather than the molecular gas phase in PDRs. The latter upper limits on the CO-dark molecular gas reservoir are consistent with the upper limit of \(\sim 10^3\) M\(_{\odot}\) derived based on the non-detection of [C ii] line emission in NGC 205.

The [C ii]-based upper limits of the molecular gas mass (\(M_{\text{H}_2}\) ≤ 1×10\(^4\) M\(_{\odot}\)) in NGC 205 are smaller compared to the H\(_2\) masses probed by CO (\(M_{\text{H}_2}$$\sim$$2.8-29.1\times10^3\) M\(_{\odot}\)). We thus conclude that the CO-dark molecular gas fraction is small in NGC 205 and that the CO line emission traces the bulk of molecular gas. Given that the ISM conditions are very similar in NGC 185, we believe that the latter argument can also be applied to NGC 185.

4.3 Warm molecular gas

The detection of rotational transitions of molecular hydrogen with the Spitzer IRS spectrometer (Marleau et al. 2010) suggests the presence of a reservoir of warm molecular gas in the centre of NGC 185, significantly warmer than the PDR component traced by [C ii] and [O i]. Based on the observed intensities of rotational H\(_2\) transitions for the three Spitzer IRS points in NGC 185 (see Fig. 1) reported by Marleau et al. (2010), we infer the temperature and column density of the warm molecular gas phase. Different mechanisms are capable of exciting H\(_2\) molecules, among which radiative excitation by massive stars with photon energies \(\phi \lesssim 13.6\) eV in PDRs, and shock excitation in molecular outflows and supernova remnants are the most important contributors.

The detection of rotational H\(_2\) transitions up to S(7) (with excitation temperatures up to 5828 K) seems unlikely to be driven by strong radiation (given the soft radiation field G\(_0\) ∼ 1-3 derived from dust SED modelling, De Looze et al. 2016a) and suggests that the highest H\(_2\) transitions are mainly shock excited. We, therefore, restrict the fitting of representative temperatures and column densities to the lower rotational levels of H\(_2\) (S(0) to S(2)) which are generally in collisional equilibrium (Burton et al. 1992).

Figure 7 (top row) presents the excitation diagrams for the central, north and south region in NGC 185, respectively. Excitation diagrams visualise the distribution of different level populations described by the column density of the upper state \(N_u\) divided by the statistical weight \(g_u\) of that level population as a function of the upper state energy level \(E_u/k\). For the construction of this excitation diagram, we have assumed that optical depth effects are negligible, which should be appropriate given the low metal abundance of NGC 185.

The best fit to the S(0), S(1) and S(2) lines results in a temperature \(T \sim 180\) K and column density \(N_{\text{H}_2} \sim 2.0 \times 10^{18}\) cm\(^{-2}\) in the central region of NGC 185. Within the Spitzer IRS extraction area (35.7′ × 10.7′), the column density corresponds to a mass \(M_{\text{H}_2} \sim 111\) M\(_{\odot}\) of warm molecular gas. This warm molecular gas mass should be regarded as a lower limit, since the area covered by the IRS slit is limited. A similar analysis of the lower H\(_2\) transitions in the excitation diagram for the IRS slit positions observed in the north and south of the galaxy indicates warm molecular gas masses of \(M_{\text{H}_2} \sim 44\) M\(_{\odot}\) (for best fitting parameters \(T \sim 190\) K and \(N_{\text{H}_2} \sim 8.0 \times 10^{17}\) cm\(^{-2}\)) in the northern pointing and \(M_{\text{H}_2} \sim 87\) M\(_{\odot}\) (for best fitting parameters \(T \sim 190\) K and \(N_{\text{H}_2} \sim 1.6 \times 10^{18}\) cm\(^{-2}\)) towards the south of NGC 185. The temperatures derived for the different regions in NGC 185 are lower compared to the average temperatures \(T \sim 350-380\) K derived for low-metallicity star-forming dwarf galaxies in Cormier et al. (2014) due to the harder and stronger radiation fields in those star-forming dwarfs, but similar to the cold molecular gas temperatures \(T \sim 150\) K derived for normal spiral galaxies (Roussel et al. 2007).

For the determination of the best-fitting temperature and column density from the observed excitation diagram, we assumed that the condition of local thermal equilibrium (LTE) is fulfilled for the lowest H\(_2\) transitions. Under LTE conditions, we expect to derive lower excitation temperatures for ratios of transitions with lower energy upper levels for an ortho-to-para density ratio of 3 (Burton et al. 1992) or, explicitly, \(T(S(1)-S(2)) < T(S(1)-S(3)) < (T(S(2)-S(3)))\). Following the procedure in Roussel et al. (2007), we can determine the excitation temperature of consecutive transitions as a function of the ortho-to-para ratio (OPR) and, hereby, verify whether the diagram shows departures from thermalisation of ortho-to-para levels. Figure 7 (bottom panels) shows the determined excitation temperatures as a function of OPR for each pair of transitions from S(0) to S(3), for the central, north and south IRS positions in NGC 185. The red-colored region satisfies the thermalisation condition. The thermalisation of H\(_2\) transitions up to S(3) seems satisfied only for the central region. Given that the S(3) - S(2) ratio is not consistent with OPR = 3 for the northern and southern regions, the higher rotational transition of H\(_2\) in...
these cases no longer satisfies collisional equilibrium and is likely excited by shocks.

Given the violation of the LTE conditions in the north and south IRS positions of NGC 185, we might overestimate the excitation temperature (due to a shock contribution) and underestimate the warm molecular gas mass in those regions. Even though the entire volume of warm molecular gas could not be traced due to the limited *Spitzer* IRS coverage, the observed warm-to-cold molecular gas fractions (ranging from 0.001 to 0.01) are one to two orders of magnitude lower than the typical warm-to-cold gas fractions reported by Roussel et al. (2007). We, therefore, do not expect to find massive reservoirs of warm molecular gas in NGC 185.

Due to the lack of IRS spectra for NGC 147 and NGC 205, we are not able to put constraints on the warm molecular gas reservoir in those galaxies.

### 4.4 Ionised gas

We estimate the ionised hydrogen mass from the observed Hα luminosity (L_{Hα} \sim 1.3 \times 10^{38} \text{erg s}^{-1}, Martínez-Delgado et al. 1999) in NGC 185 and convert it into an H ii mass (see Eq. 5 from Finkelman et al. 2010) assuming an electron temperature T_e = 10^4 \text{K} and electron density N_e = 8,300 cm^{-3} (which is the mean electron density determined for three PNe in NGC 185 by Gonçalves et al. 2012). The resulting H ii mass M_{HII} = 1 M_\odot is negligible compared to the neutral gas mass in NGC 185.

Similarly, the 1σ noise level (2.5 \times 10^{-17} \text{erg s}^{-1} \text{cm}^{-2} \text{arcsec}^{-2}) in the Hα image of NGC 205 (Young & Lo 1997) can be converted into a 3σ upper mass limit M_{HII} \lesssim 1 M_\odot assuming an electron temperature T_e = 10^4 \text{K} and electron density N_e = 5,300 cm^{-3} (which is the mean electron density of PNe determined by Gonçalves et al. 2014).

We are not aware of any Hα observations for NGC 147 which would allow us to put a constraint on the ionised gas mass in this galaxy.

### 4.5 Hot X-ray gas

The non-detections of X-ray emission from NGC 147 and NGC 185 (Brandt et al. 1997), and NGC 205 (Welch et al. 1998) allow us to put a constraint on the reservoir of hot gas in these dwarf spheroidal galaxies. We calculate the upper X-ray gas mass limit based on the prescriptions from Roberts et al. (1991) and the X-ray and B-band8 luminosities of the galaxies. We find 1σ upper limits on the X-ray gas mass of \lesssim 0.2, 0.2, 3.8 \times 10^4 M_\odot for NGC 147, NGC 185, and NGC 205, respectively.

### 4.6 Total gas mass

For the computation of the total gas mass, we combine H i gas, CO-traced and CO-dark molecular gas, ionised and hot X-ray gas masses, and the warm molecular gas reservoir cooled by H_2 rotational lines (see Table 3). The latter gas reservoirs combine to total gas masses of M_{H_2} = 1.9 \times 10^5 M_\odot and 8.6 \times 10^5 M_\odot (corrected by a factor of 1.36 to account for helium) for NGC 185 and NGC 205, respectively, and an upper limit of M_{HI} \lesssim 2.7 \times 10^8 M_\odot for NGC 147, assuming Galactic X_{CO} conversion factors. Using metallicity-dependent X_{CO} factors, the total gas masses are up to three times higher with gas masses of M_{HI} = 5.5 \times 10^8 M_\odot and M_{H_2} = 2.5 \times 10^9 M_\odot for NGC 185 and NGC 205, and an upper limit of M_{HI} \lesssim 2.7 \times 10^9 M_\odot for NGC 147. If we assume Galactic X_{CO} factors, the gaseous reservoirs in NGC 185 and NGC 205 are dominated by the atomic H i gas component, while a metallicity-dependent X_{CO} factor would imply molecular gas reservoirs that are 3 to 4 times more massive than the atomic hydrogen content.

### 5 STAR FORMATION EFFICIENCY

Based on the gas mass measurements from Section 4, we can link the reservoir that is available for star formation to the actual star formation rate, to learn more about the efficiency of gas consumption in dwarf spheroidal galaxies. We derive total molecular gas depletion time scales \tau_{dep} = \Sigma_{gas}/\Sigma_{SF}, which is the time needed to exhaust the current total (H i+H_2) and molecular (H_2) gas reservoir. Assuming that most of the gas content is located in the central regions (150 pc \times 90 pc) where recent star formation (6.6 \times 10^{-4} M_\odot yr^{-1}) took place, we derive gas depletion time scales of \tau_{H+H_2} \sim 0.3 \text{Gyr} (0.8 \text{Gyr}) and \tau_{H_2} \sim 0.05 \text{Gyr} (0.6 \text{Gyr}) for a Galactic (H band luminosity-dependent) X_{CO} factor for NGC 185. Due to the lack of any recent star formation activity and the non-detection of any gas in NGC 147, it is impossible to calculate a gas depletion time scale for this galaxy.

We use constraints on the SFR \sim 7 \times 10^{-4} M_\odot yr^{-1} (Monaco et al. 2009) in the central 28'' \times 26'' region of NGC 205. We calculate the total gas mass (2.0 \times 10^4 M_\odot) in this central region of NGC 205 based on the atomic hydrogen mass (M_{HI} \sim 7.6 \times 10^8 M_\odot) of two central H i clumps (Young & Lo 1997) and the molecular gas mass (M_{H_2} \sim 6.8 \times 10^4 M_\odot, assuming a Galactic X_{CO} factor) from the central CO pointing of Welch et al. (1998), scaled by a factor of 1.36 to include helium. Using a H-band luminosity-dependent X_{CO} factor (12.5 \times 10^{20} \text{cm}^{-2} [\text{K km s}^{-1}]^{-1}) would imply a molecular gas reservoir of 4.2 \times 10^5 M_\odot. We derive gas depletion time scales of \tau_{H+H_2} \sim 0.3 \text{Gyr} (1.0 \text{Gyr}) and \tau_{H_2} \sim 0.1 \text{Gyr} (0.8 \text{Gyr}) for a Galactic (H band luminosity-dependent) X_{CO} factor for NGC 205.

Based on these gas mass depletion time scales, the dwarf spheroidal galaxies, NGC 185 and NGC 205, are forming stars more actively in comparison to galaxies on the Kennicutt (1998) relation. At the current depletion time scale, the entire molecular gas reservoir (based on a Galactic X_{CO} factor) would be exhausted within less than 100 Myr. For metallicity-dependent X_{CO} factors, the star formation efficiencies are more comparable to normal spiral galaxies, but molecular gas depletion time scales still about a factor of 2 lower compared to the average \Sigma_{H_2} \sim 2 \text{ Gyr} in a sample of nearby spiral galaxies derived by Leroy et al. (2013). Although the level of star formation in NGC 185 (SFR \sim 6.6 \times 10^{-4} M_\odot) and NGC 205 (SFR \sim 7 \times 10^{-4} M_\odot) is very different from the star formation rates observed in normal star-forming galaxies (1-10 M_\odot yr^{-1}), the SFR conditions
in the centres of those dSphs do seem to approach the star-forming conditions observed in local spirals (and might be even more efficient). Independent evidence for a high star formation efficiency in NGC 185 was derived from its observed abundance [O/Fe] ratio (0.8 dex, Gonçalves et al. 2012), which indicates a higher SNe II rate compared to SNe Ia. The positive [O/Fe] ratio suggests that most of the gas has been consumed on short time scales.

Alternatively, we might be observing these two dSph galaxies towards the end of their recent star formation episode, having already burned most of their initial gas reservoir and resulting in an artificially high SFE estimate. We also caution that the SFE predictions might be affected by stochastic effects due to the small number of clouds detected within these galaxies.

6 GAS-TO-DUST MASS RATIO

Combining all gas and dust mass measurements (see Table 3), we derive estimates of the global gas-to-dust mass ratios GDR∼37 in NGC 185 and GDR∼48 in NGC 205. Using metallicity-dependent X_Co factors, the global gas-to-dust mass ratio would increase to GDR∼107 for NGC 185 and GDR∼139 for NGC 205. Since the H i gas is more extended compared to the dust in NGC 185 and NGC 205 (see Figures 2 and 4, respectively), the gas-to-dust mass ratio might become even smaller on local scales. These global values are lower than the average Galactic gas-to-dust mass ratio ∼130 (Draine & Li 2007). Based on the observed trend of increased gas-to-dust mass ratios with decreasing metallicity (e.g., Lisenfeld & Ferrara 1998; James et al. 2002; Hunt et al. 2005; Engelbracht et al. 2008; Galliano et al. 2008; Galametz et al. 2011; Magrini et al. 2011; Rémy-Ruyer et al. 2014), these low gas-to-dust mass ratios are considered even more exceptional, where a simple GDR ∝ Z^{-1} scaling would imply a GDR∼370 for NGC 185 and GDR∼520 for NGC 205.

Similarly low gas-to-dust mass ratios were observed in the elliptical galaxy, NGC 4125 (Wilson et al. 2013), and the dust-lane lenticular galaxy, NGC 5485 (Baes et al. 2014). The low gas-to-dust mass ratio in NGC 4125 was attributed to the rapid heating of gas to temperatures >10^4 K, faster than the evaporation of cold dust in this galaxy (Wilson et al. 2013). Such a scenario seems, however, unlikely for NGC 185, where the warm-to-cold molecular gas fractions (0.001-0.01) are much lower than observed in more massive star-forming galaxies. Also the non-detection of X-ray emission (see Section 4.5) in NGC 185 and NGC 205 is able to put an upper limit on the reservoir of hot gas (≤2.5 × 10^4 M⊙).

None of the chemical evolution models, including interstellar grain growth (Asano et al. 2013) and accounting for a wide variation of star formation histories (Zhukovska 2014) (see Figures 8 and 9 in Rémy-Ruyer et al. 2014), predict a gas-to-dust ratio as low as that observed in these dSphs considering its metal abundance. Since these low GDRs clearly deviate from theoretical model predictions, it is worth investigating the origin of the discrepancy between model and observations.

First, we consider possible caveats in the determination of total gas and dust masses. Given that the H i and CO observations are sufficiently deep to detect faint emission (Young & Lo 1997; Young 2001), we are confident that the current H i and CO data sets will not miss a massive reservoir of atomic or molecular gas. The warm molecular gas

Figure 7. Top: Observed H$_2$ excitation diagrams in the central (left), north (middle), and south (right) IRS pointings for NGC 185. The red line and symbols indicate the best fitting model with excitation temperature, $T_{\text{ex}}$, and column density, $N_{\text{H}_2}$, fitted to the first three H$_2$ rotational transitions S(0), S(1), and S(2)), for an ortho-to-para ratio of 3. Bottom: Diagram of the excitation temperatures derived for different pairs of rotational H$_2$ transitions. The excitation temperatures should increase monotonically with higher order transitions to be compatible with the thermalization of H$_2$ lines.
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7 THE ISM MASS BUDGET

In this section, we discuss the origin of gas and dust reservoirs in NGC 147, NGC 185 and NGC 205. Here, we compare the gaseous reservoirs detected in these galaxies to theoretical predictions from a simple closed-box model.

7.1 Theoretical gas consumption and replenishment

Based on prescriptions of Faber & Gallagher (1976), Sage et al. (1998) and Welch et al. (1998) estimated the gas mass returned to the ISM by planetary nebulae in the three dwarf spheroidal galaxies NGC 147 (6-11×10⁵ M⊙), NGC 185 (8-17×10⁵ M⊙) and NGC 205 (23×10⁵ M⊙), which are similar to or in excess of the current gas content in those galaxies. As a proof of concept, we redo these calculations for the dwarf spheroidal NGC 185⁹ based on a simple chemical evolution model with a closed-box approximation to account for the gas and dust mass returned by planetary nebulae and supernovae. In this simple model, we calculate the gas and dust mass that has been returned by the intermediate age population (2-3 Gyr) based on the best fitting star formation histories (SFH) presented by Martins et al. (2012) which were optimised to fit the abundance ratios of PNe, the age-metallicity relation and the total galaxy mass at the present day. Figure 9 shows their two best fitting SFHs (left panel) and the cumulative SFHs (right panel). The latter corresponds well to the cumulative SFH presented by Geha et al. (2015) that was derived from colour-magnitude diagrams based on deep V and I band Hubble Space Telescope ACS observations. Also the average current SFR~2.9-3.8×10⁻³ M⊙ yr⁻¹ measured over a time period of 1 Gyr, is consistent with the SFR derived by Martínez-Delgado et al. (1999) (SFR~6.6×10⁻³ M⊙ yr⁻¹) considering that the latter value only accounts for star formation that took place in the central regions of NGC 185.

During the simulation, we track the gas consumption, dust production and return of gaseous material to the ISM based on these SFHs at individual time steps of 10 Myr. At every time step, the contribution from stars with lifetimes \( \tau_m = t - t_0 \) (with \( t_0 \) the age at which the galaxy was born) is taken into account. The stellar lifetimes for stars of a different mass and metallicity are calculated based on the parametrisation of Raiteri et al. (1996). The dust yields are taken from Zhukovska et al. (2008) and Bianchi & Schneider (2007) for intermediate (0.8 M⊙<M<8 M⊙) and high mass (12 M⊙<M<40 M⊙) stars, respectively. The gas yields from van den Hoek & Groenewegen (1997) and Woosley & Weaver (1995) are used for intermediate mass and massive stars, respectively. We interpolate between the intermediate and high mass estimates to derive dust and metal yields for stars with masses 8 M⊙<M<12 M⊙. We neglect stars more massive than 40 M⊙ since they will collapse to form black holes at the end of their lives and have a negligible contribution to the enrichment of the ISM. For our calculations, we assume a Salpeter (1955) IMF with a slope of -2.35 within a mass range from 0.1 M⊙ to 100 M⊙.

9 We refrain from redoing the calculations for NGC 147 and NGC 205 due to the lack of sufficient constraints on their recent star formation histories.

Figure 8. The Kennicutt-Schmidt relation between the gas surface density and the SFR surface density with a representative sample of spiral and starburst galaxies from Kennicutt (1998) indicated as black asterisks and diamonds, respectively. The locations of metal-poor star-forming dwarf galaxies studied by Cormier et al. (2014) are indicated with green crosses in the K-S diagram (we omitted two galaxies with highly uncertain molecular gas masses). We only included the dwarfs from Cormier et al. (2014) with constraints on H I and H₂ masses, and scaling CO intensities with metallicity-dependent \( X_{CO,Z} \) factors to obtain the latter masses. The dwarf spheroidal galaxies under analysis in this paper, NGC 185 and NGC 205, are marked as red squares and blue triangles. Empty symbols represent total gas masses (H +H₂) with Galactic \( X_{CO} \) conversion factors, while filled symbols indicate total gas surface densities calculated with \( H \) band luminosity dependent \( X_{CO} \) factors. The black solid line represents the K-S relation \( \Sigma_{SFR} = A \Sigma_{gas}^N \) with \( N = 1.4 \) as found by Kennicutt (1998) where \( \Sigma_{gas} \) is the total gas (H +H₂) surface density, while the green dashed line represents the average molecular gas depletion time scale ~ 2 Gyr in a sample of nearby spiral galaxies derived by Leroy et al. (2013).

masses might be underestimated due to model assumptions and/or insufficient observational coverage. It is, however, unrealistic to assume that the H₂ observations with Spitzer can account for a substantial massive gas reservoir given the low warm-to-cold molecular ratio (see Section 4.3). The presence of a massive ionised gas reservoir is also unlikely given the warm-to-cold molecular ratio (see Section 4.3). The presence of a massive ionised gas reservoir is also unlikely given the weak Hα emission from NGC 185. The non-detection of [C i] in NGC 205 implies that the CO-dark molecular gas content is insignificant compared to the H₂ in NGC 205 implies that the CO-dark molecular gas content is insignificant compared to the H₂ mass traced by CO.

Although the dust masses in NGC 185 and NGC 205 have been robustly measured in De Looze et al. (2016a) and De Looze et al. (2012), the lack of knowledge on the dust composition and dust mass absorption coefficients makes the derived dust masses uncertain by at least a factor of 2. Even with this uncertainty factor of two, the main cause for the low gas-to-dust mass ratios seems hard to explain based on a lack of observational constraints and/or inaccuracies in the ISM mass predictions. We attribute the low gas-to-dust mass ratios to a combination of possible effects including efficient dust production and long-term grain survival (see De Looze et al. 2016a and Section 7.1), and the removal of part of the gas mass from the galaxy (see Section 7.2).
Running the simulation with an initial gas mass of $M_{\text{gas}}(t=0)=10^{5.6} \, M_\odot$ and metal abundance $[\text{O}/\text{H}](t=0)=10^{-4}$ (consistent with the initial conditions used by Martins et al. 2012), we derive a gas mass $(3-6\times10^5 \, M_\odot)$ returned to the ISM since the second burst of star formation initiated $\sim3.5$ Gyr ago until the current epoch. The total gas reservoir at the current epoch is estimated to be $1.1\times10^6 \, M_\odot$. With an observed gas mass $(1.9-5.5\times10^5 \, M_\odot$, see Section 4) that is two to five times smaller than predicted by our simple closed box model (and up to 3 times smaller than the gas mass returned to the ISM during the last two SF episodes), we argue that the closed box approximation does not fit the observational constraints. Similarly, De Looze et al. (2012) showed that the current gas mass reservoir in NGC 205 is too low compared to predictions of the gas mass returned by planetary nebulae. The non-detection of a gaseous reservoir in NGC 147 furthermore seems unlikely given the population of evolved stars in this galaxy (Davidge 2005). Based on a comparison of the observed dust and gas reservoirs in NGC 185 with a simple closed box model, we argue the low gas-to-dust mass ratio and gas deficiency result from gas removal processes. This gas removal could be induced by internal mechanisms (e.g., supernova explosions, stellar winds) and/or tidal interactions (see Section 7.2).

In De Looze et al. (2016a) we showed that the observed dust content is higher compared to the dust mass produced by AGB stars and supernovae during the last 100 Myr (which is the estimated dust survival time) in NGC 185. Based on the closed box model presented in this paper, we predict the production of up to 400 $M_\odot$ during the last 100 Myr. To account for the observed dust mass in NGC 185 ($5.1\times10^5 \, M_\odot$), we would require an efficient dust production during the last 1.6 Gyr without any grain destruction. The latter dust survival time is significantly higher than the estimated dust lifetime in NGC 185 (50-100 Myr). In De Looze et al. (2016a), we had argued that grain growth in the dense ISM phases could be an additional source of dust production, but the mechanisms that would enable the accretion of material onto grain surfaces in the ISM are not well understood (Ferrara et al. 2016). Other than longer dust survival times, the metal production in current nucleosynthesis models, and the dust yields of AGB stars and supernovae in dust nucleation models might be underestimated.

### 7.2 Gas removal

Gas removal can result from internal mechanisms (e.g., supernova explosions, stellar winds), or external influences (e.g., hydrodynamical or gravitational interactions). Based on analytic/numerical models for dark matter halos with the inclusion of stellar feedback (Ferrara & Tolstoy 2000), a total blow-away of the entire gaseous medium is only possible for dark matter halos of $M_h \sim 5 \times 10^8 \, M_\odot$ (Ferrara & Tolstoy 2000). With galaxy masses of $M_h \sim 7.2 \times 10^8 \, M_\odot$ and $M_h \sim 5.6 \times 10^8 \, M_\odot$ (Geha et al. 2010) for NGC 185 and NGC 147, the dwarf spheroidal galaxies might lose some (but not all) gas to the intergalactic medium. The latter scenario is consistent with chemical evolution models which require efficient galactic winds to reproduce observed gas masses and abundances for the dSph galaxy population (e.g., Lanfranchi & Matteucci 2004, 2010; Martins et al. 2012). Some of the metal-enriched gas expelled by galactic winds is assumed to rain back down on the galaxy disk according to a “galactic fountain” mechanism that is able to flatten the metallicity gradient in those dSphs (De Young & Heckman 1991; Ferrara & Tolstoy 2000; Barazza & Bingelli 2002).

While this “galactic fountain” effect might work for heavier galaxies, we argue that any gas expelled from these Andromeda dSph dwarfs will easily escape from the galaxy if heated to sufficiently high temperatures. Using the total galaxy masses (including baryonic and dark matter) for NGC 147, NGC 185 and NGC 205 from De Rijcke et al. (2006) within 2 effective radii ($R_{\text{eff}}$), we derive escape velocities$^{10}$ that range from 57 to 91 km s$^{-1}$ at a radius of $2^*R_{\text{eff}}$. By heating the gas to sufficiently high temperatures, the thermal gas velocity of a gas with a temperature of $T_{\text{kin}} = 10^6 \, K$ ($v_{\text{th}} = 90 \, \text{km} \, \text{s}^{-1}$)$^{11}$ would be sufficient for the gas no longer to be gravitationally bound to the galaxy. This simple calculation shows that if the hot gas is blown out by supernova feedback and/or stellar winds to large radii, it might be able to escape from the galaxy if heated to sufficiently high temperatures. The typical hot X-ray halo of gas that provides more massive galaxies with fresh gas supplies for star formation does not seem to be present in those lower metallicity dwarfs which is observationally supported by the non-detections of X-ray emission in these dwarfs (see Section 4.5). The presence of dust and the metal enrichment (0.2-0.3 dex) over the last $\sim8$ Gyr (Gonçalves et al. 2012) in the central regions of NGC 185 is consistent with the absence of “galactic fountains” which would distribute the metals throughout the galaxy’s disk.

But this observed central concentration of metals is also compatible with a scenario of external influences that mostly remove the metal-poor H i gas from the outer galaxy parts (Valluri & Jog 1990). Tidal interactions with other satellite galaxies or Andromeda can also potentially remove the gas from the outer galaxy regions in NGC 185 and entirely strip the gas from NGC 147. Recent observations from the Pan-Andromeda Archaeological Survey (PAndAS) reveal isophotal twinning and the emergence of extended tidal tails in NGC 147, but do not show any evidence for tidal effects on the stellar light profiles of NGC 185 (Crnojević et al. 2014). The asymmetric H i distribution, combined with its small extent up to only 1/4th of its Holmberg radius (Young & Lo 1997) might be an indication for tidal effects having played an important role in the evolution of NGC 185 in the past. Being located at an angular distance of 12 degrees from M 31, NGC 185 and NGC 147 are currently beyond the tidal influence radius of Andromeda$^{12}$. Given their small angular separation (~1°), the two galaxies have been argued to form a gravitationally bound pair (van den Bergh 1998; Geha et al. 2010). Based on their carbon star pop-

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$^{10}$ The escape velocity is calculated from $v_{\text{esc}} = \sqrt{2GM/R}$ using the total galaxy mass, $M$, the distance to the centre of mass, $R=2^*R_{\text{eff}}$, and the gravitational constant, $G$.

$^{11}$ The thermal gas velocity for a gas with kinetic temperature $T_{\text{kin}} = 10^6 \, K$ is calculated from $v_{\text{th}} = \sqrt{T_{\text{kin}}} \times 1/\text{m}$ using the Boltzmann constant, $k_B$, the mass of a hydrogen atom, $m$, and the gas temperature $T_{\text{kin}} = 10^6 \, K$.

$^{12}$ For NGC 185 and NGC 147, the tidal radius has been calculated to be between 10-12 kpc or, thus, beyond 25 effective radii (Geha et al. 2010).
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7.3 Galaxy evolution

Although the three dwarf spheroidal galaxies probably share a similar evolutionary history (driven by galactic winds and/or tidal interactions), their different ISM conditions (i.e., central ongoing star-formation in NGC 185 and NGC 205, and the lack of any detectable ISM material in NGC 147) shows that similar mechanisms can result in a variety of morphological outcomes (e.g., Ryé et al. 2013) depending on the efficiency of galactic winds and the orbit of the galaxy (e.g., Kazantzidis et al. 2011).

Chemical evolution models seem to require high galactic wind efficiencies to explain the build up of gas and metals in these galaxies (e.g., Lanfranchi & Matteucci 2004, 2010; Martins et al. 2012), while tidal stirring (Mayer et al. 2001) and galaxy threshing (Bekki et al. 2001) have been put forward as the most important mechanisms for the formation of dwarf spheroidals and ultracompact dwarfs in low-density group environments based on galaxy simulations. Also observational evidence of tidal influence for galaxies residing in group environments (e.g., Paudel & Ree 2014) supports these theoretical simulations.

Given the wide range of resulting end products and the continuous influence of environmental effects on most galaxies residing in cluster and group environments, it has hard to constrain the progenitor galaxies of these dwarf spheroidal galaxies in the Local Group (Lisker et al. 2013). Rather than the transformation of dwarf irregular into dwarf elliptical galaxies, the present-day dwarf galaxy population might originate from the same common progenitor population that experienced a different evolution due to differences in dark matter content, stellar mass and/or environments (e.g., Ferrara & Tolstoy 2000; Tolstoy et al. 2009; Sawala et al. 2012). The only way to properly constrain the evolutionary history of the population of dwarf spheroidal galaxies that is present-day observed in group and cluster environments, is through a combination of observations probing their stellar populations, star formation history, chemical enrichment, kinematic properties (e.g., Tolstoy et al. 2009) and orbital parameters (e.g., Howley et al. 2008; Watkins et al. 2013).

8 CONCLUSIONS

We make an inventory of the gas content in three low-metallicity dwarf spheroidal galaxies of the Local group (NGC 147, NGC 185 and NGC 205) based on an extensive set of ancillary observations. We present new Nobeyama CO(1-0) observations that cover the previously unexplored regions in the south of NGC 205, and we use Herschel SPIRE FTS [C ii] observations to limit the fraction of CO-dark gas in NGC 205. Based on Herschel observations of the far-infrared fine-structure lines [C ii] and [O i] towards the central regions NGC 185, we analyse the typical conditions of the ISM in dSphs.

We compute total gas masses of $M_g = 1.9-5.5 \times 10^5 M_\odot$ (NGC 185) and $M_g = 8.6-25.0 \times 10^5 M_\odot$ (NGC 205) within the limits of uncertainty on the $X_{CO}$ factors, by combining the mass reservoirs of atomic, cold and warm molecular, ionised and hot X-ray gas. Non-detections result in an upper gas mass limit of $M_g \leq 0.3-2.2 \times 10^5 M_\odot$ for NGC 147.
Our new NRO 45m CO(1-0) map of the southern regions in NGC 205 shows that most of the molecular gas is distributed towards the north and centre. The non-detections of the [C ii] 1-0 and 2-1 line transitions in the SPIRE FTS spectra implies that the CO-dark gas fraction is negligible in NGC 205 compared to the molecular gas mass traced by CO, which is also consistent with the lower [C ii]/CO ratios (2-4×10^4) in dSphs compared to low-metallicity star-forming dwarf galaxies with [C ii]/CO ratios of a few times 10^5.

Photo-dissociation models suggest a soft radiation field (G_0~1-30) and moderate hydrogen gas density (n_H~10^3-10^4 cm^{-3}) to explain the observed [C ii], [O i] and total-IR emission in NGC 185. The detection of several high excitation lines implies that also a dense PDR phase with small filling factor is present, or alternatively requires shocks to excite the lines. The high [C ii]/TIR~1.5% and [C ii]+[O i]/TIR~2% ratios indicate that the photoelectric efficiency is high, which might be explained by a high PAH abundance and/or low level of grain charging in NGC 185. The star formation rate densities and current gas reservoirs in NGC 185 and NGC 205 places these galaxies above the main sequence of star forming galaxies. The short molecular gas depletion time scales imply that fuel for star formation will run out in less than a few 100 Myr in these dSphs.

We derive global gas-to-dust mass ratios of GDR~37-107 and GDR~48-139 which are at the low end of the average Milky Way ratio of GDR~130 and significantly lower compared to the expected ratios of GDR~370 and GDR~520 for the metal abundances in NGC 185 (0.36Z_⊙) and NGC 205 (0.25Z_⊙), respectively. Based on a simple closed box model, we confirm that these dSphs are gas deficient and that the dust has a longer dust survival time (~1.6 Gyr) in these galaxies which can also explain their anomalous GDR. We conclude that part of the gas content has been removed from the dSph satellites in the recent past. We believe that efficient galactic winds (combined with the heating of gas to sufficiently high temperatures in order for it to escape from the galaxy) and/or environmental interactions with neighbouring galaxies are responsible for the gas removal from NGC 147, NGC 185 and NGC 205.

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