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<th><strong>Publication Year</strong></th>
<th>2019</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Acceptance in OA@INAF</strong></td>
<td>2021-02-19T16:32:41Z</td>
</tr>
<tr>
<td><strong>Title</strong></td>
<td>Rise and fall of molecular clouds across the M33 disk</td>
</tr>
<tr>
<td><strong>Authors</strong></td>
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<tr>
<td><strong>DOI</strong></td>
<td>10.1051/0004-6361/201834437</td>
</tr>
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<tr>
<td><strong>Journal</strong></td>
<td>ASTRONOMY &amp; ASTROPHYSICS</td>
</tr>
<tr>
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Rise and fall of molecular clouds across the M 33 disk

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Received 16 October 2018 / Accepted 4 January 2019

ABSTRACT

We carried out deep searches for CO line emission in the outer disk of M 33, at \( R > 7 \) kpc, and examined the dynamical conditions that can explain variations in the mass distribution of the molecular cloud throughout the disk of M 33. We used the IRAM-30 m telescope to search for CO lines in the outer disk toward 12 faint mid-infrared (MIR) selected sources and in an area of the southern outer disk hosting MA1, a bright HII region. We detect narrow CO lines at the location of two MIR sources at galactocentric distances of about 8 kpc that are associated with low-mass young stellar clusters, and at four locations in the proximity of MA1. The paucity of CO lines at the location of weak MIR-selected sources probably arises because most of them are not star-forming sites in M 33, but background sources. Although very uncertain, the total molecular mass of the detected clouds around MA1 is lower than expected given the stellar mass of the cluster, because dispersal of the molecular gas is taking place as the HII region expands. The mean mass of the giant molecular clouds (GMCs) in M 33 decreases radially by a factor 2 from the center out to 4 kpc, then it stays constant until it drops at \( R > 7 \) kpc. We suggest that GMCs become more massive toward the center because of the fast rotation of the disk, which drives mass growth by coalescence of smaller condensations as they cross the arms. The analysis of both HI and CO spectral data gives the consistent result that corotation of the two main arms in this galaxy is at a radius of 4.7 ± 0.3 kpc, and spiral shock waves become subsonic beyond 3.9 kpc. Perturbations are quenched beyond 6.5 kpc, where CO lines have been detected only around sporadic condensations associated with UV and MIR emission.

Key words. ISM: clouds -- Galaxy: kinematics and dynamics -- galaxies: ISM -- galaxies: individual: M 33 -- ISM: molecules

1. Introduction

Our knowledge of molecular clouds and the processes in the interstellar medium (ISM) that favor the birth of stars is mostly based on Galactic studies. The increase in resolution and sensitivity has enabled recent extragalactic surveys to study the formation of stars as galaxies evolve and as a function of galaxy mass, morphology, and metallicity. Nearby galaxies are an ideal place where a global picture of the disk is complemented by detailed observation of the ISM and star-forming (hereafter SF) sites. In this context, particular attention has been given to low-luminosity Local Group galaxies with subsolar metallicity: M 33 in the north and the Large Magellanic Cloud (LMC) in the south. The spiral galaxy M 33 is particularly interesting because it is a blue SF galaxy with no evident sign of ongoing or past interactions, as shown by the most recent proper motion measurements and past orbital history (Patel et al. 2017; van der Marel et al. 2019). It is a relatively unperturbed spiral with no bulge (Corbelli & Walterbos 2007) and an extended warped outer disk (Corbelli et al. 2014). This makes it an ideal laboratory to study how the gas settles in the disk and develops instabilities that condense and form stars and/or to determine the role of feedback in triggering a new generation of stars (Dobbs et al. 2018; Corbelli et al. 2018).

The investigation of individual SF complexes in nearby galaxies and all-disk surveys at infrared and millimeter wavelengths (through facilities such as Spitzer, Herschel, IRAM, and ALMA) reveals how the ISM and the star formation process differ in chemically young environments as compared to more evolved spirals. The molecular cloud mass spectrum steepens, the conversion of molecular gas into stars is faster, and the CO-to-H₂ ratio decreases in lower metallicity environments (Gratier et al. 2012, 2010; Rosolowsky 2005; Fukui et al. 2008; Verley et al. 2009; Gil de Paz et al. 2007; Dib et al. 2011). M 33 is an ideal object to study these differences because its metallicity is only a factor two below solar (Magrini et al. 2010) and it retains a clear disk spiral morphology such that morphological and chemical differences are not mixed. Because of the limited differences, we can continue to use the same tracers as in large spirals. M 33 represents a sort of stepping stone toward smaller objects where chemical differences are more extreme and mixed with morphological changes.

Recently, Corbelli et al. (2017) have estimated the duration of the life cycle of giant molecular clouds (hereafter GMCs) in M 33 using the all-disk CO \( J = 2–1 \) survey (Druard et al. 2014) to identify 566 GMCs in the SF disk, and a mid-infrared (hereafter MIR) selected sample of 630 young stellar cluster candidates (hereafter YSCCs) from the catalog of Sharma et al. (2011). The GMCs spend 4 Myr in the inactive phase and 10 Myr in the active SF phase. Sources are in the embedded phase (detected only in the infrared) during only 2 Myr of the active phase, and for the remaining time YSCCs break through the cloud and become also detectable in Hα or UV. The correlation between GMCs and MIR-selected YSCCs is remarkable: in the active phase, all GMCs are associated with MIR sources.

There is, however, a non-negligible fraction of MIR sources that are not hosted by GMCs, and this fraction increases moving radially outward. One possibility is that these MIR sources are associated with less massive molecular clouds below the detection limit, which form low-mass clusters that are often
undetectable in Hα because of the lack of massive stars. Through the MIR source catalog and CO pointed observations, Corbelli et al. (2011) have found low-mass SF complexes associated with molecular clouds that are weak in CO $J = 1-0$ and $J = 2-1$ line emission. A key question related to this issue is to understand variations in the molecular mass spectrum beyond galactocentric radii of about 4 kpc in M 33 (Braine et al. 2018). We know that the mass spectrum of molecular clouds changes across the disk of a galaxy (Rosolowsky 2005; Gratier et al. 2012; Heyer & Dame 2015), but the reason for this, and whether other properties change, is still an open question (Bigiel et al. 2010; Colombo et al. 2014; Freeman et al. 2017; Kobayashi et al. 2017). The onset of instabilities and the ability of the gas to cool and fragment may be not efficient enough to create massive complexes at large galactocentric radii, or it might just be that the spiral pattern cannot accumulate gas and merge clouds to make more massive complexes beyond corotation, although disk instabilities can still trigger the formation of filaments (Elmegreen & Elmegreen 1995; Dobbs et al. 2018).

Outer disks are key places to understand galaxy evolution: in the local Universe, ΛCDM models predict that large spirals like M 31 do not accrete much gas into the disk, while low-mass galaxies, such as M 33, experience an inside-out growth and feed star formation through cold gas streams from the intergalactic medium that settle into the disk (Magrini et al. 2007; Williams et al. 2009; Kereš et al. 2009; Dekel et al. 2013; Fitts et al. 2018). It is therefore important to understand how pristine outer gas mixes with the galaxy ISM, and in particular, if and how star formation and metal enrichment occur beyond the bright SF disk and if this occurs continuously or in a burst. Imaging in V and I band with the Subaru/Suprime-Cam of a few fields of M 33 in the outer regions (Grossi et al. 2011) has revealed a pervasive diffuse evolved stellar population (>1 Gyr), but also a population of younger stars (100–200 Myr) where Hα overdensities are present in the outer disk. An interesting output of MIR source selection in the M 33 area is that low-luminosity sources are also present in correspondence with the outer disk beyond the SF edge where the Hα surface brightness drops (Verley et al. 2009; Sharma et al. 2011). One possibility is that a background population of faint MIR sources is mixed in projection with truly M 33 SF sites and that this becomes the dominant population at large radii. It may also be, however, that some of these faint MIR sources are small SF sites in the outer disk of M 33. In this paper we use sensitive IRAM-30 m observations to understand the nature of these faint MIR sources. It is conceivable to detect CO emission in molecular clouds just beyond the SF edge in M 33 because the metallicity is about one-third solar (Grossi et al. 2011; Magrini et al. 2010) and the UV field is weak (Thilker et al. 2005). It is still unclear which are the conditions that favor the growth of molecular clouds beyond the SF edge of a galaxy, and whether it is possible to find them in the extreme outer disk (Digel et al. 1994; Snell et al. 2002; Braine et al. 2007).

In Sect. 2 we summarize some properties of GMCs and MIR sources across the M 33 disk. In Sect. 3 we describe CO observations in the outer disk for a selected MIR sample and around a bright HII region. In Sect. 4 we discuss some implications of the detected and undetected CO lines, such as the molecular mass of condensations in the outer disk and the nature of faint MIR sources. In Sect. 5 we show results relative to disk dynamics that can be linked to the observed radial distribution of molecular clouds. Section 6 concludes after we summarize the main results.

![Fig. 1. Mean value of GMC mass in dex in radial bins of galactocentric distance from data in the GMC catalog of Corbelli et al. (2017).](image-url)

**2. Distribution of GMCs and MIR sources across the disk of M 33**

M 33 has a gaseous disk with holes and dense filaments related to optically visible flocculent spiral arms. Two of these have more prominent and numerous HII regions, one is in the northern approaching side and the other is in the southern receding side. We examine three distinct radial ranges, $R < 4$ kpc, $4 < R < 7$ kpc, and $R > 7$ kpc, and we refer to these as inner disk (dominated by the two main arms), the intermediate disk, and the outer disk. In this paper we refer to the SF disk of M 33 to indicate the area within galactocentric distances of 7 kpc (inner + intermediate disk). The outer disk encloses the extreme regions of the optical disk close to $R_3$ and the warp, and it is beyond the Hα luminosity drop (Kennicutt 1989; Verley et al. 2009). In this section we review the changes in the mean mass of GMCs and the 24 µm flux of MIR sources across the M 33 disk. We also describe the selection of the MIR sample for deep CO observations in the outer disk.

The GMC catalog comprises 566 clouds with masses between $2 \times 10^4$ and $2 \times 10^5 M_\odot$ and radii between 10 and 100 pc (Corbelli et al. 2017). We recall that for the existing GMC catalog and in the rest of this paper, the CO-to-H$_2$ conversion factor used is constant and equal to $4 \times 10^{20} K^{-1} \text{ km}^{-1} \text{ cm}^2$ unless stated otherwise. The estimated mass of 490 clouds is above the survey completeness limit of $6.3 \times 10^9 M_\odot$. Braine et al. (2018) have shown that the GMC mass spectrum becomes steeper moving towards large galactocentric radii, and the maximum mass of GMCs is also a factor 2 smaller than in the inner disk. A similar trend has been found for the 24 µm flux of the MIR source in the M 33 area by Sharma et al. (2011): the cumulative distribution steepens in the intermediate disk, where the maximum source luminosity is lower than in the inner disk. The ratio of molecular cloud mass to MIR flux density at 24 µm does not show a clear radial trend: it has a mean value of about $4 \times 10^4 M_\odot$ mJy$^{-1}$ and a large dispersion (of about 0.7 dex) at all radii.

The number of GMCs per unit area decreases continuously with radius across the disk. However, the average mass of GMCs decreases radially in the inner disk (which hosts 410 GMCs), but then it flattens in the intermediate disk (hosting 152 GMCs) and drops in the outer disk (where only 4 GMCs are found since the all-disk survey does not cover much of the outer disk). Figure 1 shows this radial trend. The analysis of Gratier et al. (2017), dedicated to investigating whether and how CO traces
molecular cloud masses in the SF disk, confirms the rather constant fraction of dark gas across the SF disk that is, that the CO-to-H$_2$ conversion factor does not increase at large galactocentric radii in the SF disk. This ensures that the observed trend for the mean molecular mass in the inner and intermediate disk, inferred for a constant CO-to-H$_2$ conversion facto, is indeed real. The increase in mean GMC mass in the inner disk can be caused by the rotation of the spiral arm pattern, which collects clouds into more massive complexes inside 4 kpc. This mechanism can break beyond a certain radius, the corotation radius. Farther out, beyond 6.5 kpc, the disk is stable according to the Toomre stability criterion (Corbelli 2003). Alternatively, the shear may break the perturbations apart at large radii and leave only GMCs below a certain mass. We examine these possibilities in Sect. 5 after discussing the results of additional CO observations of selected targets in the outer disk in the next sections.

The mean mass of molecular clouds hosting MIR sources is weakly related to the intensity of the 24 µm flux, $F_{24}$, for bright sources. This is shown in Fig. 2, where we compute the mean GMC mass in bins of 24 µm flux intensity. For $F_{24} > 5$ mJy, the mean GMC mass increases as the 24 µm flux of the hosted source increases. However, this trend has a large scatter, and furthermore, it disappears for faint MIR sources or if we consider only MIR sources in the intermediate disk, which is devoid of bright MIR sources (open red squares in Fig. 2). This can be due to the limited sensitivity and completeness of the CO all disk survey, and it needs further investigation by deeper CO searches around faint MIR sources. However, when we extrapolate the trend observed for $F_{24} > 5$ mJy, the expected mean mass of a GMC hosting an MIR source with $F_{24} = 0.1$–1 mJy is about $10^5 M_\odot$, only one order of magnitude below the mean mass of GMCs that are associated with the brightest MIR sources ($F_{24} \sim 10^3$ mJy). It is then conceivable to detect molecular gas associated with faint MIR sources through pointed observations, even though the CO-to-H$_2$ ratio might decrease in the outer disk. Molecular line emission has been detected in the SF disk of M 33 by Corbelli et al. (2011) at the location of compact MIR sources with $3 \leq F_{24} \leq 21$ mJy at the level of 0.3 K km s$^{-1}$. Estimated molecular cloud masses range between $10^4$ and $10^5 M_\odot$. The detected lines suggest that low-mass GMCs might be ubiquitous around MIR sources in the SF disk of M 33, despite the large spread in CO-to-$F_{24}$ flux ratio. This needs to be examined for fainter MIR sources and in the outer disk.

In the rest of this section, we select a faint MIR sample in the outer disk for deep pointed CO observations. These observations are presented in the next section, where we additionally describe the results of a CO $J = 2–1$ line map around a bright H$_\alpha$ source in the outer disk.

### 2.1. Multiwavelength data

In analyzing the data of M 33, we assumed a distance of 840 kpc (Freedman et al. 1991; Gieren et al. 2013), which implies a linear scale of 4.1 pc per arcsecond.

Dust emission at MIR wavelengths has been investigated through the InfraRed Array Camera (IRAC) and the Multiband Imaging Photometer (MIPS) on board Spitzer. The complete set of IRAC (3.6, 4.5, 5.8, and 8.0 µm) and MIPS (24, and 70 µm) images of M 33 is described by Verley et al. (2007). To investigate the ultraviolet (UV) continuum emission of M 33, we used Galaxy Evolution Explorer (GALEX) data, in particular those distributed by Gil de Paz et al. (2007). To trace ionized gas, we adopted the narrow-line H$\alpha$ image of M 33 obtained by Greenawalt (1998) and described in detail in Hoopes & Walterbos (2000).

The H$\alpha$ and FUV surface brightnesses in M 33 decrease radially with a scale length of about 2 kpc out to about 6.5 kpc (Verley et al. 2009). Beyond this radius, they experience a sharper radial decline (see also Kennicutt 1989). The distribution of the neutral atomic gas traced by 21 cm line emission in M 33 has been mapped by combining Very Large Array (VLA) and the Green Bank Telescope (GBT), and results are described by Corbelli et al. (2014). The atomic gas distribution starts to warp beyond the SF disk, and the surface mass density drops at $R_{25}$ (which is about 8.6 kpc), where the warp becomes severe. We used the tilted ring model fitted to the 21 cm velocity field (Corbelli et al. 2014) to estimate galactocentric distances for sources in the warped outer disk.

### 2.2. Selection of the MIR sample in the outer disk

From the catalog of 912 MIR sources in the M 33 area (Sharma et al. 2011), we selected 99 sources that might be associated with SF sites at galactocentric distances 7.5 < $R$ < 10.8 kpc and that have not been listed as M 33 variable stars or have a Milky Way star as optical counterpart. The inner radial cutoff was chosen to avoid overlaps with the M 33 all-disk CO $J = 2–1$ survey covering the SF disk (Druard et al. 2014), while the outer radius was dictated by the full coverage of Spitzer-IRAC maps of M 33 and of other available maps (GALEX, H$\alpha$). The analysis of CO observations of a previous sample of faint, compact MIR sources in the SF disk of M 33 has revealed the importance of IRAC and MIR color-color diagram as a diagnostic tool to distinguish MIR sources that are truly SF sites from evolved stellar objects, such as AGB stars and background galaxies (Corbelli et al. 2011). In the SF disk, CO $J = 1–0$ and 2–1 lines have been detected around all MIR sources with a characteristic spectral energy distribution between 3.6 and 24 µm (see their Fig. 5). The main-beam integrated temperature for the CO $J = 2–1$ lines for the selected MIR sources in the SF disk is between 0.7 and 2 K km s$^{-1}$ with peaks between 0.1 and 0.5 K (Corbelli et al. 2011) that are uncorrelated with the intensity of 24 µm flux (in the range 1–21 mJy).

To estimate the energy density in IRAC bands, we performed aperture photometry for the 99 selected sources with a fixed aperture size of 8 arcsec. We refer to Sharma et al. (2011) for details on the photometry at 24 µm, in H$\alpha$, FUV, and NUV bands.
Sources that were selected for pointed CO observations, while the asterisk in the squares highlights sources with detected CO emission as described in the next section. In the left panel of Fig. 4 we use orange asterisks to indicate the location of the GMCs in the SF disk. The ellipse encloses the SF disk area and has been drawn for PA = 23° and i = 54° (de Vaucouleurs et al. 1991). Selected sources may have galactocentric distances that differ from what the ellipse position suggests because of the change in orientation of the disk beyond 7 kpc.

In Fig. 5 we plot the location of selected MIR sources over a smoothed version of the 21 cm line map (equivalent beam FWHM = 130 arcsec) in order to recover emission from the outer disk. The atomic gas map shows that even though all sources are located beyond the SF edge of M 33, the majority of them still overlap the bright atomic disk, before the 21 cm surface brightness drops and the faint warped outer disk takes place. The dark contour level is at 5 Jy beam\(^{-1}\) km s\(^{-1}\), which corresponds to a face-on value column density of about 2 \(\times 10^{20}\) cm\(^{-2}\). Most of the sources lie in regions of which can shield molecules from the weak interstellar dissociating radiation field. Metallicities (expressed as 12 + log(O/H)) are expected to be roughly a factor 3–4 below solar at galactocentric distances of the sources and imply a CO-to-H\(_2\) conversion factor larger than the Galactic in the solar neighborhood (Amorín et al. 2016), that is, between 1.3 and 2 times the conversion factor used for the SF disk (which reads \(X_{\text{CO}} = 4 \times 10^{20}\) K\(^{-1}\) cm\(^{-2}\), Gratier et al. 2017).

### 3. CO observations

In this section we describe the observations of CO \(J = 1–0\) and CO \(J = 2–1\) at the position of the selected MIR sources in the outer disk. We also present a 5 arcmin\(^2\) map of the CO \(J = 2–1\) emission around a bright HII region in the southern side of the outer disk. We refer to this area as the southern field.

#### 3.1. Pointed observations of the MIR-selected sample

We searched for CO emission using the IRAM-30 m telescope at the location of all sources in Table 1. The CO \(J = 1–0\) and \(J = 2–1\) lines were observed during March 2016 with an FWHM beam of 21.4 arcsec at 115 GHz and of 10.7 arcsec at 230 GHz. The \(J = 2–1\) line is less likely to be affected by beam dilution than the \(J = 1–0\) line, but so far out in the disk, the excitation conditions may favor the lower transition. We observed all sources using the wobbler switching mode, making sure not to have CO emission in the reference beam. The FTS backend with a spectral resolution of 195 kHz was used, corresponding to channel widths of 0.5 km s\(^{-1}\) at 115 GHz and 0.25 km s\(^{-1}\) at 230 GHz. The VESPA backend system with 78.1 kHz resolution (0.25 km s\(^{-1}\)) was also used at 115 GHz, but the HI noise level was higher than for the FTS backend when data were smoothed at the same spectral resolution, therefore we only discuss the FTS data. All spectra were smoothed to a spectral resolution of 0.5 km s\(^{-1}\), and data from both polarizations were averaged. The beam and forward efficiencies used to convert antenna temperatures into main-beam temperatures are 0.71 and 0.95 at 115 GHz, respectively, and 0.65 and 0.92 at 230 GHz, respectively.

Table 2 summarizes the CO \(J = 1–0\) and \(J = 2–1\) data. The identification number of the MIR source in each pointed observation is in given in Col. 1. In Cols. 2 and 3 we show the integrated line brightness per beam I of the \(J = 1–0\) and \(J = 2–1\) lines, respectively, in main-beam temperature units. In Cols. 4 and 5 we display the mean velocity V of the two
The peak intensity value \( P \) is given in Cols. 8 and 9, and the rms noise level for the CO \( J = 1-0 \) and \( J = 2-1 \) spectra, smoothed at 2 km s\(^{-1}\) resolution, is presented in Cols. 10 and 11, respectively. The \( I \), \( V \), and \( W \) values are those of the best Gaussian fit to the line after smoothing the data to a resolution of 0.5 km s\(^{-1}\). The integrated line brightness obtained by summing the flux in each channel inside the signal spectral window is given in parentheses, and it can be seen that the difference with the integral of the Gaussian fitted line is on the same order as the fit uncertainty. Using the rms noise, we have estimated 4 rms upper limits for the integrated line emission at locations of sources with no detectable signal. The values quoted in Table 2 are for a 8 km s\(^{-1}\) spectral window.

In Fig. 6 we show the detected lines. Only 2 out of the 12 MIR sources were detected, and the peak velocities of the \( J = 1-0 \) and \( J = 2-1 \) correspond to within 0.5 km s\(^{-1}\), therefore we can assume that the two lines come from the same cloud. The lines are narrow, and the \( J = 2-1 \) to the \( J = 1-0 \) integrated line brightness ratio varies: it is 0.5 for s799 and 1.2 for s892. The small size of the MIR source and the high \( J = 2-1/1-0 \) ratio with respect to the standard 0.8 value (Druard et al. 2014) suggests that beam dilution affects source s892. On the other hand, the weakness of the radiation field in these outer regions can easily cause the CO \( J = 2-1 \) line to be dimmer and lower the \( J = 2-1 \) to \( J = 1-0 \) ratio, as is observed for source s799 (see next section for more details on models for the detected gas).

We also pointed the telescope at five positions close to source s892 (s892−o1, o2, o3, o4, and o5) whose offsets in arcsec for RA and Dec are \((11.5, -1.0), (10.5, -11.4), (36, 22.5), (63.36.2), \) and one position close to source s555 (s555−o1), whose offset is \((7, -7)\). No lines were detected in any of the offset locations. The upper limits are on the same order as the fluxes detected on source at (0,0) offset, and we conclude that the cloud associated with source s892 does not have brighter peaks in nearby locations. This is supported by the null detection after stacking the offset spectra, as discussed in the next section. The position of source s555 is in the lower right corner of the southern field, as discussed in the next subsection, and its upper limit confirms that the emission in the southern field is not very extended.
3.2. Map of the southern field

A region centered at RA = 01:33:06 Dec = 30°11′30″ (RA = 23.2750° Dec = 30.1917°), close to the position of a large HII region in the extreme south of M 33, was included in the CO J = 2–1 observations of the all-disk survey (Druard et al. 2014). This region was observed separately because the position of the center of M 33 in the sky exceeds the IRAM 83° elevation limit for about 40 min every day. Defining the southern region as a separate source enabled us to observe it during about 25 of the 40 min that would have been lost each day (the remaining time was used to check pointing). It was observed at 82.8° elevation on average and is slightly beyond the southern limit of the map presented in Druard et al. (2014). It was therefore not presented in Druard et al. (2014).

The bright HII region in the southern field, also known as MA1 (Mayall & Aller 1942), lies at a galactocentric distance of 7.4 kpc, and it is one of the few HII regions that are located beyond the drop of the average Hα surface brightness. The metal content of this outer HII region has been investigated, and the most recent estimate for its oxygen abundance is 12+log(O/H) = 8.28 dex (Magrini et al. 2010). This HII region is coincident with the MIR source identified by Sharma et al. (2011) with ID number 562, which has a flux of 9.2 mJy and a size of 4.4 arcsec at 24 μm. It hosts a stellar cluster whose stellar mass and age have been estimated to be about 6000 M⊙ and 8 Myr by Sharma et al. (2011). This HII region is much brighter than any other in the MIR sample selected in the outer disk.

The southern field of M 33 was observed as described in Druard et al. (2014), using on-the-fly mapping in CO(2–1) with the HERA multibeam receiver. Figure 7 shows the Hα emission in color with the 100 μm PACS emission in black contours and the positions where CO emission is well above the noise. The thick red contour indicates the extent of the CO map. The four CO spectra with a high enough signal-to-noise ratio are overplotted, and the triangles indicate the corresponding position in the disk. Spectra within 5 arcsec of the nominal position were summed to improve the signal-to-noise ratio. This broadens the beam only slightly since these spectra are all within the half-power size of a single beam. The nominal position of the spectra is given by the pixel with the highest signal-to-noise ratio. A white contour shows where N_{HI} = 1.8×10^{21} cm^{-2}, that is, where the HI column density is high. In the southern field the HI column density peaks in between the two SF regions and not where star formation is taking place, which is likely due to the transition from HI to H2 and to the expansion of the HII region shell, which compresses the surrounding neutral ISM and thus enhances the local density.

Each box in Fig. 7 shows the CO(2–1) spectrum in white and the HI line temperature (divided by 1000) in light blue. The CO spectra are presented on the T_{mb} scale and all spectra are in Kelvin. The CO emission is strongest close to the HII region center. All CO line widths are typical of single GMC, although they
Table 1. Properties of the MIR-selected sample.

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<td>1.7</td>
<td>0.87 $\pm$ 0.02</td>
<td>0.49 $\pm$ 0.03</td>
<td>...</td>
<td>...</td>
<td>9.2</td>
<td></td>
</tr>
<tr>
<td>s787</td>
<td>23.8474</td>
<td>30.7463</td>
<td>2.0</td>
<td>2.62 $\pm$ 0.02</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>8.5</td>
</tr>
<tr>
<td>s799</td>
<td>23.1572</td>
<td>30.7673</td>
<td>1.4</td>
<td>0.54 $\pm$ 0.01</td>
<td>0.33 $\pm$ 0.03</td>
<td>34.7</td>
<td>37.3</td>
<td>37.0</td>
<td>7.8</td>
</tr>
<tr>
<td>s854</td>
<td>23.2726</td>
<td>30.9742</td>
<td>1.4</td>
<td>0.45 $\pm$ 0.01</td>
<td>0.26 $\pm$ 0.02</td>
<td>36.8</td>
<td>36.9</td>
<td>7.7</td>
<td></td>
</tr>
<tr>
<td>s892</td>
<td>23.7087</td>
<td>31.1582</td>
<td>1.4</td>
<td>0.45 $\pm$ 0.01</td>
<td>0.37 $\pm$ 0.03</td>
<td>35.7</td>
<td>37.8</td>
<td>37.5</td>
<td>8.1</td>
</tr>
<tr>
<td>s905</td>
<td>23.6735</td>
<td>31.2885</td>
<td>1.9</td>
<td>2.77 $\pm$ 0.02</td>
<td>1.80 $\pm$ 0.06</td>
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<td>...</td>
<td>10.1</td>
<td></td>
</tr>
<tr>
<td>s907</td>
<td>23.4811</td>
<td>31.3279</td>
<td>2.0</td>
<td>1.94 $\pm$ 0.02</td>
<td>0.43 $\pm$ 0.03</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>9.8</td>
</tr>
</tbody>
</table>

Notes. The identification number of each source in the MIR-selected sample is listed in Col. 1, and the relative celestial coordinates are presented inCols. 2 and 3. The estimated source radius is given in Col. 4 and the flux at 24 $\mu$m in Col. 5. The 8 $\mu$m flux is listed in Col. 6, and the source luminosity in the H$\alpha$ line and in the near and far continuum UV are given in Cols. 7–9, respectively. In the last column we show the source galactocentric distance.

Table 2. CO line pointed observations of the MIR-selected sample and Gaussian fits to detected lines.

<table>
<thead>
<tr>
<th>ID</th>
<th>$I_{1-0}$</th>
<th>$I_{2-1}$</th>
<th>$V_{1-0}$</th>
<th>$V_{2-1}$</th>
<th>$W_{1-0}$</th>
<th>$W_{2-1}$</th>
<th>$P_{1-0}$</th>
<th>$P_{2-1}$</th>
<th>rms$_{1-0}$</th>
<th>rms$_{2-1}$</th>
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<tr>
<td>s537</td>
<td>&lt;77</td>
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<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>4.8</td>
<td>3.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>s542</td>
<td>&lt;93</td>
<td>&lt;70</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>5.8</td>
<td>4.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>s555</td>
<td>&lt;75</td>
<td>&lt;75</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>4.7</td>
<td>4.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>s555−o1</td>
<td>&lt;140</td>
<td>&lt;117</td>
<td>...</td>
<td>...</td>
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<td>...</td>
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<td>7.3</td>
<td></td>
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<td>s631</td>
<td>&lt;75</td>
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<td>s672</td>
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<td>5.0</td>
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<tr>
<td>s771</td>
<td>&lt;83</td>
<td>&lt;83</td>
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<td>5.2</td>
<td>5.2</td>
<td></td>
<td></td>
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<tr>
<td>s787</td>
<td>408 ± 45</td>
<td>202 ± 19</td>
<td>−179.1</td>
<td>−179.5</td>
<td>3.7</td>
<td>2.4</td>
<td>104</td>
<td>79</td>
<td>8.8</td>
<td>4.8</td>
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<tr>
<td>s854</td>
<td>&lt;87</td>
<td>&lt;89</td>
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<td>...</td>
<td>...</td>
<td>...</td>
<td>5.4</td>
<td>5.6</td>
<td></td>
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<tr>
<td>s892</td>
<td>150 ± 23</td>
<td>179 ± 11</td>
<td>−272.4</td>
<td>−272.8</td>
<td>2.2</td>
<td>3.0</td>
<td>65</td>
<td>57</td>
<td>6.1</td>
<td>4.5</td>
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<tr>
<td>s892−o1</td>
<td>&lt;171</td>
<td>&lt;128</td>
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<td>...</td>
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<td>...</td>
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<td>8.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>s892−o2</td>
<td>&lt;134</td>
<td>&lt;140</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
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<td>8.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>s892−o3</td>
<td>&lt;158</td>
<td>&lt;132</td>
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<td>...</td>
<td>...</td>
<td>...</td>
<td>9.9</td>
<td>8.3</td>
<td></td>
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</tr>
<tr>
<td>s892−o4</td>
<td>&lt;144</td>
<td>&lt;146</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>9.0</td>
<td>9.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>s892−o5</td>
<td>&lt;205</td>
<td>&lt;131</td>
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<td>...</td>
<td>...</td>
<td>...</td>
<td>12.8</td>
<td>8.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>s905</td>
<td>&lt;101</td>
<td>&lt;63</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>6.3</td>
<td>3.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>s907</td>
<td>&lt;85</td>
<td>&lt;61</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>5.3</td>
<td>3.8</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes. The ID of the MIR source in each pointed observation is given in Col. 1. InCols. 2 and 3 we show $I$, the integrated line brightness per beam of the $J = 1−0$ and $J = 2−1$ detected lines, respectively (in parentheses we add the values obtained by summing the flux in each channel) or their upper limits. InCols. 4 and 5 we display the mean velocity $V$ of the detected lines, inCols. 6 and 7 we list the relative line widths $W$, and inCols. 8 and 9 the peak intensity values $P$. In the last two columns we show the rms noise level for the CO $J = 1−0$ and $J = 2−1$ spectra smoothed at 2 km s$^{-1}$ resolution.

are broader than most spectra in the outer disk of M 33, as for sources s799 and s892 (but see also Braine et al. 2012), presumably due to the high level of star formation and to the evolution of the HII region. Table 3 gives the integrated intensities and Gaussian fit results in main-beam temperature units. The beam and forward efficiencies used to convert antenna temperatures into main-beam temperatures at the time of these observations are 0.55 and 0.92 at 230 GHz. The uncertainties are from the fitting program in CLASS$^1$. Uncertainties on the integrated intensities inCol. 2 can be calculated as $\Delta I = 1.5 \times \text{rms} \times \sqrt{W_{2-1} \times 2.6}$ where rms is given inCol. 8 and $W_{2-1}$ inCol. 5. These uncertainties are similar to those in the GaussArea task in CLASS. We did not subtract the 2.6 km s$^{-1}$ channel width, therefore the $W_{2-1}$ values inCol. 5 are upper limits.

4. Radial decline of the molecular cloud mass in M 33

In this section we discuss the results of detected and undetected CO line emission. We averaged spectra of undetected sources to

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$^1$ See http://www.iram.fr/IRAMFR/GILDAS/
cloud surface brightness with the beam for the intrinsic line ratio $R_{21}$ was estimated only when the $J = 1–0$ line was also detected, otherwise $R_{21}$ was an input value.

We estimated the metallicity $Z$ at the location of sources s799 and s892 using the galactocentric distance $R$ and the oxygen abundance radial gradient of Magrini et al. (2010). Following Amorim et al. (2016), we assumed a $Z^{-1.5}$ metallicity dependence of $X_{\text{CO}}$ and write

$$\log \frac{X_{\text{CO}}}{2 \times 10^{20}} = 12.85 - 1.5 \left(12 + \log \frac{O}{H}\right) = 0.1 + 0.066R. \quad (1)$$

For $R = 3$ kpc, this formula gives $X_{\text{CO}} = 4 \times 10^{20}$ K$^{-1}$ km$^{-1}$ s$^{-1}$ cm$^{-2}$, the commonly used conversion factor for the SF disk of M33, and hence it well approximates the average value of $X_{\text{CO}}$ derived for the inner and intermediate disk by Gratier et al. (2017). These authors found that for M33 the CO-to-H$_2$ conversion factor is independent of radius out to about 6 kpc, but beyond this radius, the lack of GMCs prevents any definitive conclusion.

We list in Table 4 the estimated molecular cloud parameters for the two detected sources in the MIR sample using the three methods. Estimated cloud masses include He and heavier elements. For the ratio method we used three different values of $R_{21}$ and quote the results when a value of the cloud size $D$ satisfies the assumptions (i.e., that gives the observed $J = 1–0$ and $J = 2–1$ integrated line brightness for the assumed intrinsic line ratio $R_{21}$). For source s892, all methods give similar cloud mass estimates, on the order of $2 \times 10^4 M_\odot$, while the cloud extent is not well determined. The low $I_{2–1}/I_{1–0}$ ratio observed at the location of source s799 might be due to the low-excitation conditions of the gas, because the SF source is weak in FUV and H$\alpha$ emission. At this location, the cloud mass can be as high as $10^5 M_\odot$ and more extended than the beam FWHM at 115 GHz. Smaller sizes and lower masses are inferred using the virial or the fill method, which predict low values of $R_{21}$.

The expected stellar masses of YSCCs associated with sources s799 and s892 are 200–300 $M_\odot$, as determined by the spectral energy distribution fits (Sharma et al. 2011), and they imply a total stellar cluster-to-cloud mass ratio lower than 0.02.

The molecular cloud masses associated with sources s799 and s892, although very uncertain, confirm the paucity of giant molecular complexes beyond the SF edge and the decrease in mean value of molecular cloud mass from the intermediate to the outer disk. We underline that the results shown in Table 4 are relative to a CO-to-H$_2$ conversion factor that is $8.2 \times 10^{20}$ and $8.6 \times 10^{20}$ K$^{-1}$ km$^{-1}$ s$^{-1}$ cm$^{-2}$ for sources s799 and s892, respectively. These values are about a factor 2 higher than that inferred for the SF disk by Gratier et al. (2017) and used by Corbelli et al. (2017) and by Braine et al. (2018). Although beyond the SF edge the conversion factor may increase with respect to the SF disk as a result of more extreme physical and chemical conditions, it is unlikely that molecular clouds associated with sources s799 and s892 are much more massive than what we quote in Table 3. This implies that the average mass and size of perturbations that occasionally grow in the outer disk drop beyond the SF edge. The low mass of the YSCCs that are hosted by these clouds provides additional support to this conclusion.

Using the virial and fill method, we also quote in Table 4 the cloud mass at the four positions listed in Table 3 in the southern field. The metallicity was determined for MA1...
Fig. 7. Southern field Hα emission in color, with 100 µm PACS emission in black contours. Four CO spectra in the southern field where the signal is well above the noise are shown, with the precise positions indicated with red or black triangles. The 21 cm spectrum at the location of the detected CO line is shown in cyan. The thick red contour indicates the extent of the CO map. The white contour between the Hα emitting zones shows the $N_{\text{HI}} = 1.8 \times 10^{21} \, \text{cm}^{-2}$ column density level (in the rest of the region, the HI column densities are lower than the contour value).

Table 3. Gaussian fits to the CO $J = 2–1$ integrated line brightness per beam for the detected emission in the southern field.

<table>
<thead>
<tr>
<th>Name</th>
<th>Offset arcsec</th>
<th>$I_{2-1}$ mK km s$^{-1}$</th>
<th>$V_{2-1}$ km s$^{-1}$</th>
<th>$W_{2-1}$ km s$^{-1}$</th>
<th>$P_{2-1}$ mK</th>
<th>$\Delta V_{2-1}$ km s$^{-1}$</th>
<th>rms$_{2-1}$ mK</th>
</tr>
</thead>
<tbody>
<tr>
<td>562a</td>
<td>(∼562,−1704)</td>
<td>427 ± 84 (375)</td>
<td>−79.9 ± 0.4</td>
<td>4.3 ± 1.1</td>
<td>94</td>
<td>−83,−77</td>
<td>16.9</td>
</tr>
<tr>
<td>562b</td>
<td>(∼676,−1677)</td>
<td>595 ± 104 (492)</td>
<td>−102.4 ± 0.6</td>
<td>7.2 ± 1.4</td>
<td>77</td>
<td>−107,−98</td>
<td>16.1</td>
</tr>
<tr>
<td>562c</td>
<td>(∼−610,−1696)</td>
<td>927 ± 100 (825)</td>
<td>−83.6 ± 0.3</td>
<td>6.0 ± 0.7</td>
<td>144</td>
<td>−89,−80</td>
<td>17.2</td>
</tr>
<tr>
<td>562d</td>
<td>(∼−555,−1669)</td>
<td>341 ± 67 (336)</td>
<td>−86.5 ± 0.5</td>
<td>4.5 ± 0.9</td>
<td>70</td>
<td>−91,−82</td>
<td>13.4</td>
</tr>
</tbody>
</table>

Notes. The name of detected cloud clump is given in Col. 1. Column 2 gives the cloud clump offset with respect to the center of M 33. Column 3 gives the CO line intensity in main-beam temperature units computed as the area of the best-fit Gaussian function, in parentheses we list the values obtained by summing the flux in each channel of the selected spectral window. Columns 4 and 5 give the central velocity and the line width of the Gaussian fits, respectively. The signal peak and spectral window are given in Cols. 6 and 7, respectively. Column 8 gives the per channel noise level of the spectra (for a channel width of 2.6 km s$^{-1}$).

in the southern field to be 12+log(O/H) = 8.28 (Magrini et al. 2010), and this implies a CO-to-H$_2$ conversion factor $X_{\text{CO}} = 5.4 \times 10^{20} \, \text{K} \cdot \text{km} \cdot \text{s} \cdot \text{cm}^{-2}$, according to the above equation. The strong radiation field of the HII region in the southern field suggests that very low values of $R_{21}$ are excluded. The total molecular hydrogen mass estimated for $R_{21} = 1.2$ in the southern field is very similar for both the virial and the fill method, being $5.4 \times 10^4$ and $6.1 \times 10^4 \, M_\odot$, respectively. The total molecular hydrogen mass is in agreement with the mass of other GMCs measured in the outer disk and plotted in Fig. 1. The virial method implies more compact clouds, but as discussed later in this section, virial equilibrium is unlikely for gas in the proximity of an HII region that is not compact. Radiation from the stellar cluster breaks through the original cloud, which is swept away by the expanding ionized shell. Given the linear scaling of cloud mass with 1/$R_{21}$ for the fill methods, we estimate a total molecular mass of about $10^5 \, M_\odot$ for $R_{21} = 0.8$, which is still in agreement with a drop of the mean molecular cloud mass beyond the SF disk.

4.2. Stacking spectra

The ratio of the integrated CO $J = 1–0$ line brightness to the 24 µm source flux, $I_{1-0}/F_{24}$, is 0.76 and 0.33 K km s$^{-1}$ mJy$^{-1}$ for sources s799 and s892, respectively. These values are higher than those in the sample of Corbelli et al. (2011) for brighter MIR sources in the SF disk (0.05 < $I_{1-0}/F_{24}$ < 0.28 K km s$^{-1}$ mJy$^{-1}$). For undetected sources of the MIR sample presented in this paper, this ratio is always lower than 0.2 K km s$^{-1}$ mJy$^{-1}$ and hence well below the values for the two detected sources in the outer disk. To further lower this limit, given the lower CO-to-24 µm flux ratios measured by Corbelli et al. (2011) in the SF disk, we stacked the CO spectra of MIR sources with no detected lines.
The low rms of the stacked spectra implies that for a 8 km s\(^{-1}\) spectral window, the average ratio of the integrated CO \(J = 1-0\) line brightness to the 24\,\mu m source flux is lower than 0.02 K\,km\,s\(^{-1}\) mJy\(^{-1}\). This upper limit is more than a factor 10 lower than the measured CO-to-24\,\mu m flux ratio for the two MIR sources detected in the outer disk and lower than any measured CO-to-24\,\mu m flux ratio in the whole disk of M 33. The lack of CO detection for most of the sources in the MIR sample casts doubts on the association of the same faint MIR sources with the M 33 disk, and we address this question in the next subsection.

Table 4. Estimated properties of the detected molecular clouds in the outer disk for a metallicity-dependent CO-to-H\(_2\) conversion factor.

<table>
<thead>
<tr>
<th>ID</th>
<th>Line</th>
<th>(R_{21})</th>
<th>(D)</th>
<th>(M)</th>
<th>Method</th>
</tr>
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<tbody>
<tr>
<td>799</td>
<td>2–1,1–0</td>
<td>0.4</td>
<td>34</td>
<td>9.9</td>
<td>Ratio</td>
</tr>
<tr>
<td>799</td>
<td>1–0</td>
<td>0.15</td>
<td>9.2</td>
<td>5.1</td>
<td>Virial</td>
</tr>
<tr>
<td>799</td>
<td>2–1</td>
<td>0.15</td>
<td>9.2</td>
<td>2.2</td>
<td>Virial</td>
</tr>
<tr>
<td>799</td>
<td>2–1,1–0</td>
<td>0.26</td>
<td>11</td>
<td>5.2</td>
<td>Fill</td>
</tr>
<tr>
<td>892</td>
<td>2–1,1–0</td>
<td>0.4</td>
<td>12</td>
<td>2.1</td>
<td>Ratio</td>
</tr>
<tr>
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<td>2–1,1–0</td>
<td>0.8</td>
<td>27</td>
<td>3.0</td>
<td>Ratio</td>
</tr>
<tr>
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<td>1–0</td>
<td>0.37</td>
<td>10</td>
<td>2.0</td>
<td>Virial</td>
</tr>
<tr>
<td>892</td>
<td>2–1</td>
<td>0.32</td>
<td>5.2</td>
<td>1.9</td>
<td>Virial</td>
</tr>
<tr>
<td>892</td>
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<td>11</td>
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<td>0.8</td>
<td>2.0</td>
<td>1.5</td>
<td>Virial</td>
</tr>
<tr>
<td>562b</td>
<td>2–1</td>
<td>0.8</td>
<td>1.0</td>
<td>2.1</td>
<td>Virial</td>
</tr>
<tr>
<td>562c</td>
<td>2–1</td>
<td>0.8</td>
<td>2.2</td>
<td>3.3</td>
<td>Virial</td>
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<tr>
<td>562d</td>
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<td>0.8</td>
<td>1.4</td>
<td>1.2</td>
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<td>1.3</td>
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<td>Fill</td>
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<tr>
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<td>1.6</td>
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<td>Fill</td>
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<td>11</td>
<td>0.9</td>
<td>Fill</td>
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</table>

Notes. The CO rotational line used to infer the cloud parameters is given in Col. 2, the intrinsic CO line ratio in Col. 3, and the cloud diameter in Col. 4. The cloud mass is shown in Col. 5, and in the last column, we indicate the method used to derive the cloud parameters.

We applied the stacking procedure to all CO spectra with an offset near source s892 and independently to the ten CO spectra with undetected line emission centered at the position of MIR sources. We performed this for the CO \(J = 1-0\) and \(J = 2-1\) line separately by computing the expected frequency of the CO lines for each source. We aligned the spectra according to the expected frequencies and averaged them. We estimated the expected line frequencies from the 21 cm line velocity because 21 cm emission is present at all selected positions in the disk. Despite the very low noise in the stacked spectra, no CO lines were detected. Stacked spectra obtained by averaging individual spectra of the undetected sources after aligning them to the rest frequency of the expected CO lines. The vertical dashed line indicates the location in the spectra where a faint CO \(J = 1–0\) or CO \(J = 2–1\) line should be detected if some faint emission line were present in individual spectra.

4.3. Background source count at 24\,\mu m

The MIR source catalog of Sharma et al. (2011) contains 912 sources that lie in the sky area covered by the M 33 gaseous disk. They have 24\,\mu m fluxes above 0.2 mJy, and only 240 sources are brighter than 5 mJy. The area of the survey is approximately 0.75\,\text{deg}^2, equivalent to 161\,kpc\(^2\) at the distance of M 33. At bright flux densities, \(F_{24} \gtrsim 5\,\text{mJy}\), the background source counts increase at approximately the Euclidean rate, and we expect only 23 sources in the survey area (Papovich et al. 2004). However, the MIR source catalog in the M 33 area is far from being complete below 5 mJy because the sensitivity of the survey varies across the sky, to crowding and diffuse emission in the inner regions of M 33. Hence, both MIR sources located in the M 33 disk and background sources from more distant sources might not have been detected.

To evaluate the level of background contamination in our sample, we plot in Fig. 9 the radial decline of the number of MIR sources per unit area expressed in kpc\(^2\). Owing to the progressive radial decline of star formation per unit area in M 33, we expect that the number density of MIR that are true SF sites declines radially as well. This has been shown to be the case for the whole sample selected by Sharma et al. (2011), although the radial distribution flattens beyond 8 kpc. We selected sources with fluxes \(F_{24} > 5\,\text{mJy}\) (bright sample), and with \(5 > F_{24} > 0.2\,\text{mJy}\) (faint sample) and plot in Fig. 9 the number of sources per unit area as a function of galactocentric radius. The absence of bright sources beyond 8 kpc (open squares in Fig. 9) does not necessarily imply that star formation stops beyond this radius since SF sites might be fainter at large galactocentric radius. The filled symbols connected by the heavy line in the same figure indicate the radial trend for the faint sample, which contains the 99 sources described in Sect. 2 of this paper. The flatness of the density distribution for fainter sources beyond 8 kpc suggests that this is the likely level of background contamination, although the baryonic surface density also flattens in the outer disk. The apparent weak radial decline of the faint MIR source number density in the outer disk is uncertain because of the deconvolution procedure in the warped region (the tilted rings partially overlap), and we considered the mean value of the observed source density to estimate the background contamination.
placed at the distance of M 33) should be selected to find CO with that sources with FUV luminosities higher than 10^36 erg s^{-1} that has not been observed yet. These 4 sources lie within the selected area for IRAC colors and are within the M 33 optical radius, at galactocentric distances between 7.5 and 8.1 kpc. At a similar distance lies the only source within the selected area with FUV luminosities >10^36 erg s^{-1}, and only sources s421 and s892 of the 81 sources are clearly detected in Hα. The paucity of Hα emission can be explained by the IMF incompleteness in low-mass clusters, however, because the Ly-continuum emission decreases much more rapidly than UV emission as the stellar mass in a young cluster decreases.

We underline that in the outer disk of M 33, small SF sites are still present within the optical radius (8.5 kpc), they are rare and can be found by a careful analysis of associated UV emission and IRAC colors, as confirmed by the detection of molecular lines in their close proximity presented in this paper. If our estimate of the background contamination is correct, there might still be only a few other MIR sources in our sample with very faint FUV and CO luminosity that are SF sites in the outer disk of M 33.

4.4. Evolution of the star-forming region in the southern field

The total molecular mass recovered by mapping the southern field is about 6 × 10^4 M_⊙, as shown in Table 4 and discussed in Sect. 4.1. Most of the molecular gas emission is in the proximity of the isolated HII region in this field, which hosts a stellar cluster whose stellar mass and age have been estimated to be about 6000 M_⊙ and 8 Myr by Sharma et al. (2011). As cataloged by Relaño et al. (2013), the Hα emission of MA1 in the southern field is not compact, nor is it distributed in a pure shell (as in the case of RVP87, the HII region in the northern side of the outer disk), but is of mixed morphology. This is indicative of an intermediate age for the SF region associated with it, as confirmed by the spectral energy distribution fits by Sharma et al. (2011). The patchy location of CO peaks and the high ratio of stellar to molecular gas mass suggests that the molecular cloud is no longer contracting, but is affected by the stellar cluster feedback. The velocity shift between the CO lines and the 21 cm lines at the same location in the proximity of MA1 is larger than for the detected CO lines in the MIR sample and is consistent with this evolutionary scenario.

The cluster intermediate age is supported by dust properties: dust is still at high temperature and localized rather than being distributed farther away, such as for a more evolved shell-like HII region. The stellar cluster has a low infrared-to-FUV ratio, as found for a few other MIR sources located in the SF disk that have similar Hα morphologies, 24 μm fluxes, and stellar cluster ages. None of these sources is coincident with massive GMCs, although one is at the boundary of a cataloged cloud (s765) and others lie close to pixels where some CO emission is present. The sensitivity in the southern field map is higher than that in the all-disk survey for the SF disk of M 33, and it allows recovering weaker CO lines. In addition, cataloged GMCs have to satisfy a number of requirements concerning the spatial extent and velocity coherence of contiguous pixels, which makes it unlikely.
that molecular gas distributions as patchy as found around MA1 would be identified as one single GMC.

The low TIR/FUV ratio, cluster age, and Hα morphology suggest that in these regions star formation is close to its end and that stellar evolution is reducing the original molecular content while the cluster breaks through the gas. In a low-density environment such as the outer disk, the pressure of the hot gas and shock wave is unable to trigger new GMCs and episodes of star formation in the HII region proximity. Hence, molecular hydrogen is fading away as the young stellar cluster evolves.

5. Disk instabilities and the corotation radius

We consider the total gaseous disk of M 33, made of atomic and molecular gas, in which addition to its self-gravity feels the gravity of the stellar disk. The disk is unstable according to the Toomre criterion out to about 6.5 kpc (Binney & Tremaine 2008; Corbelli 2003). The ratio of the atomic gas to stellar dispersion in M 33 is about 0.5, because the gas FWHM is radii-

Fig. 10. Unstable perturbations in the M 33 disk. In the upper panel the long- and short-dashed lines show the most unstable wavelength according to Jeans criteria and to Toomre criteria, respectively, as a function of galactocentric radius. The continuous line indicates twice the vertical scale height for the gas. In the bottom panel the predicted molecular cloud masses for perturbations with radius equal to the vertical gaseous disk scale height are shown with a continuous line as a function of galactocentric radius. The long-dashed line indicates the mass corresponding to perturbations with radius equal to one-quarter the Jeans length.

maximum mass value is about $4 \times 10^6 M_\odot$ at 4 kpc. Although this mass is in agreement with the highest GMC masses recovered in M 33, the radial trend is opposite to what the data in Fig. 1 show at small galactocentric radii. The time for shear to tear a gas condensation apart increases radially outwards and is longer than the free-fall time throughout the SF disk, which means that shear cannot be responsible for the radial decrease of the molecular cloud mass presented in Sect. 2 either.

As shown in Fig. 10, the most unstable wavelength increases radially outward, and this justifies the radial decrease in number density of molecular clouds from the center to the outer disk. The most unstable Toomre length is indicative of the separation between filaments that form in the unstable disk. Therefore the disk instability analysis correctly predicts the observed drop in number density of molecular clouds in the stable outer disk, but it cannot explain the extra growth of individual perturbations in the inner disk where the mean GMC mass is observed to increase toward the center. In the next subsection we examine an additional mechanism, the rotation of the main arm pattern, which can play a role in driving the radial decrease in molecular complex mass in the inner disk. This decrease is not fast, and it is indicative that this mechanism will pile up only a few clouds to provide the extra growth in mass. Only close to the galaxy center is the difference between the observed and the predicted mass (bottom panel of Fig. 10) more evident. However, here the gas vertical scale height is likely underestimated by the model. Furthermore, in the central regions the ISM is highly turbulent, as the shape of the probability distribution function shows (Corbelli et al. 2018), and the high rate of star formation likely triggers the formation of new clouds and enhances their agglomeration into larger complexes by frequent episodes of gas compression.

5.2. Corotation radius

In order to derive the speed of the spiral pattern in the disk of M 33, we adopted the kinematical method developed by
Tremaine & Weinberg (1984, TW). The method was originally devised to provide a model-independent means of measuring the pattern speed of bars in S0 galaxies. It has subsequently been generalized to non-rigid patterns, that is, with a radially varying pattern speed, by Merrifield et al. (2006), and was used to estimate the pattern speed in nearby galaxies using HI or CO emission as mass tracer by Zimmer et al. (2004), for instance. It is assumed that the disk is flat and thin with negligible vertical motions; it is also assumed that the intensity in the adopted tracer, as representative of the surface density of a mass component, obeys a continuity equation along the orbit around the galactic center, meaning that there is no source or sink of the tracer. Both the inclination to the line of sight $i$ and the position angle PA are assumed to be known. Under these hypotheses, the derivation of the pattern speed is quite straightforward. First we produce zeroth- and first-moment images from the 21 cm and CO(2–1) cubes and rotate them to align the major axis horizontally (x-axis, positive to the receding SW side). After subtracting the systemic velocity $V_{\text{sys}} = -180 \text{ km s}^{-1}$, for each strip of pixels parallel to the major axis at distance $y$ from it, we evaluate the intensity-weighted line-of-sight mean velocity

$$<V(y)> = \frac{\int_{-\infty}^{+\infty} I(x,y) v_{\text{LOS}}(x,y) \, dx}{\int_{-\infty}^{+\infty} I(x,y) \, dx},$$

and similarly, the intensity-weighted mean x-position of the tracer

$$<x(y)> = \frac{\int_{-\infty}^{+\infty} x \, I(x,y) \, dx}{\int_{-\infty}^{+\infty} I(x,y) \, dx}.$$  

According to the TW method, the angular speed of the pattern is then given by

$$\Omega_p = \frac{1}{\sin i} \left(<V(y)> \cdot <x(y)>\right)^{1/2}$$

For each strip, at each of the sampled $y$, we will have a pair of $(<V(y)>$, $<x(y)>)$ values that are linearly related in case of a rigid pattern. The slope of the relation $<V(y)>$ versus $<x(y)>$ is $\Omega_p \times \sin i$.

The results are shown in Figs. 11 and 12. The point distribution is clearly linear and therefore indicative of a well-defined rigid trailing spiral pattern; in addition, the results from the two tracers are remarkably consistent. We obtain the tightest regressions, and best agreement between HI and CO results, by adopting a PA = 23° ± 2°, a value quite close to the one derived from the optical images (e.g., 22.7° in HyperLeda or 23° in de Vaucouleurs et al. 1991). From the HI we obtain $\Omega_p \times \sin i = 18.15 \pm 0.15 \text{ km s}^{-1} \text{kpc}^{-1}$, and from the CO(2–1) we get 18.05 ± 0.35 in the same units. The final estimate is then 18.13 ± 0.14 km s$^{-1}$ kpc$^{-1}$.

Using the rotation curve and the (inner) disk inclination ($i = 54°$) in Corbelli et al. (2014), we finally obtain a corotation radius $R_{\text{cor}} = 4.7 \pm 0.3 \text{kpc}$. The assigned uncertainty includes those on inclination, rotation curve, and $\Omega_p \times \sin i$. Assuming the 21 cm second moment measures the sound speed (including turbulence), we can locate the sonic point, where the velocity difference between pattern and rotating gas equals the sound speed, at a radius of 3.9 kpc. We also performed the preceding analysis separately for the two halves of the galaxy, NE and SW of the minor axis. In this case, the corotation is more external in the NE, 5.4 kpc, than SW, 4.5 kpc; we find no significant difference in the mean velocity dispersion.

We summarize the importance of the corotation radius as follows: the lack of molecular clouds in the outer disk as well as the mass distribution of GMCs across the SF disk of M-33 is consistent with the mass predicted by the growth of individual condensations in the gaseous unstable disk, except in the innermost regions, where the observed mean GMC mass increases toward the center. When we account for the fast disk rotation with respect to the arm pattern, this discrepancy is alleviated because molecular clouds can experience an extra growth as the arms collect smaller clouds into larger self-shielded complexes inside the corotation radius. The location of the corotation radius is consistent with the galactocentric radius inside which the extra growth of GMC mass is observed.

6. Summary and conclusions

We have presented the results of deep observations of CO lines at selected locations in the outer disk of M-33 to complement the
results of existing surveys of molecular clouds in the SF disk and examine possible triggers of molecular cloud mass growth across the disk of the closest blue disk galaxy. We detected CO $J = 1–0$ and $J = 2–1$ lines near the position of two MIR sources in the outer disk, at about 8 kpc from the center, which have 24 $\mu$m fluxes of only 0.5 mJy and faint UV and optical counterparts. The CO lines are very narrow, with main-beam peak temperatures of about 0.05 K. At the location of another ten selected MIR with 24 $\mu$m features of about 0.05 $\mu$m, the CO lines are very narrow, with main-beam peak temperatures of about 0.05 K. At the location of another ten selected MIR with 24 $\mu$m fluxes between 0.4 and 2.8 mJy and galactocentric distances between 7.7 and 10.4 kpc, we have only upper limits on the CO line emission that are considerably below the line brightness detected in the proximity of the other two MIR sources.

We also detect CO $J = 2–1$ lines in the proximity of MA1, one of the outermost HII regions in the south, at about 7.4 kpc from the center. We mapped the CO $J = 2–1$ line emission in an area of about 5 arcmin$^2$ and detect CO lines that imply a total molecular mass of about $6 \times 10^4 M_\odot$. The most prominent line is emitted close to the HII brightness peak where most of the dust emission is also located. The other CO lines are detected at the boundary of the HII regions: here the gas is likely compressed through shock fronts that develop as the HII region expands, and some cold gas, molecular and atomic, can be found.

It is conceivable that the paucity of CO lines in the outer disk of M 33 is enhanced by the lower metal abundance, although the metallicity gradient in the bright disk is not very steep. However, the analysis in this paper has shown that a change in the disk dynamical conditions is likely at the heart of the detected variations of molecular cloud growth across M 33. We summarize our main conclusions below.

- The speed of the spiral arm pattern in the inner disk is determined through a kinematical method applied to both HI and CO data sets. The atomic and molecular gas give consistent results: the arms of M 33 rotate at about 22.4 km s$^{-1}$ beyond the disk unstable region are rare. Stacking of CO lines near the position of two MIR sources in the far outer disk (Grossi et al. 2011), where no bright FUV knots are found, is likely the result of a past burst of star formation triggered by gas or satellite accretion (Grossi et al. 2008; Mostoghiu et al. 2018). Stellar migration from the inner disk cannot affect regions that are in the far outer disk in less than 1 Gyr (Magnani et al. 2016). CO is found at the location of few MIR sources with FUV emission in the outer disk where the azimuthally averaged HI column density is still above $1 M_\odot$ (Corbelli et al. 2014). This is consistent with the location of young stellar clusters associated with FUV knots in dwarf irregular galaxies (Hunter et al. 2016), where the larger distance and lower metallicity prevent deep local CO searches.

Acknowledgements. We would like to thank the anonymous referee for their comments and careful reading of the original manuscript. E.C. thanks Bruce Elmegreen for stimulating discussion on topics related to this paper. We acknowledge funding from the INAF PRIN-SKA 2017 program 1.05.01.88.0.

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