Formation and Evolution of Galaxy Outskirts
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Molecular gas in the outer disks of galaxies

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Abstract. Molecular gas has still only been detected beyond the R_{25} radius in a few galaxies. Is this due to the low H_2 content or to the difficulty of using Carbon Monoxide (CO) to trace H_2? Similarly, star formation (SF) decreases sharply in the outer disks of spirals although HI is often plentiful; is the decrease in SF because there is little H_2 or because the SF is very inefficient in the outer disk environment?

Existing observations suggest that while outer disk clouds tend to be smaller (steeper mass function), their CO brightness temperature is only slightly lower than in the inner disk, at least when observed with sufficiently high angular resolution. In near-solar metallicity galaxies ($Z \geqslant 0.5 Z_{sol}$), the CO does not become intrinsically difficult to detect when H_2 is present, even in the outer disk. While more observations of CO or other means of tracing H_2 in the outer disks are necessary, current data tend to show that the SF rate per unit H_2 remains approximately constant with galactocentric distance, indicating that the star formation proceeds normally but the transformation of HI into H_2 is very slow in the outer disk.

Keywords. ISM: molecules, stars: formation, Galaxies: ISM, Galaxies: Local Group, Galaxies: individual (M33, NGC4414, NGC6946)

Five galaxies have reported detections of CO beyond the nominal R_{25} radius:
Milky Way out to at least 20 kpc (*e.g.* Digel *et al.* 1994, Brand & Wouterloot 1994);
NGC 4414 out to 1.5 R_{25} (Braine & Herpin 2004);
NGC 6946 out to 1.3–1.4 R_{25} (Braine *et al.* 2007);
M 33 out to 1.1 R_{25} (Braine *et al.* 2010); and M 63 out to 1.36 R_{25} (Dessauges-Zavadsky *et al.* 2014). The extragalactic detections were only of the CO(1–0) transition except for M 33 where CO(2–1) was also detected.

Good limits are available for NGC 1058 (Braine *et al.* 2007), NGC 4625 (Watson *et al.* 2016, and M 83 (see Morokuma *et al.* in these proceedings). Other unpublished limits may well be available.

There is generally a sharp decrease in the star formation (SF) rate and the CO intensity at approximately R_{25}. The atomic gas is typically abundant beyond R_{25} so is this due to the difficulty in forming molecular gas or to the difficulty in forming stars far out in galactic disks? For a mass-to-light ratio of unity, R_{25} corresponds to 6.6 $M_\odot/pc^2$ – this is very close to the typical gas surface density at R_{25} in normal spirals as $6 \times 10^{20} H/cm^2$ is equivalent to 6.6 $M_\odot/pc^2$ when the associated Helium is included.

Interestingly, in M 33, which is a small spiral with a subsolar metallicity, the drop in star formation and CO intensity occurs significantly within R_{25} but at roughly $\Sigma_{gas} \sim \Sigma_{stars}$. Thus, a more physical definition for "outer" may be where the gas surface density exceeds the stellar. If so, then the "outer" disk is within R_{25} for very late-type galaxies but also for galaxies seen at intermediate and high redshifts.

The data for NGC 4414 and M33 suggest that the ratio of the SF rate (SFR) to H_2 mass stays roughly constant with radius even beyond the R_{25} radius. Thus, it appears that the roughly constant H_2 depletion time holds for the outer disk as well. Given the

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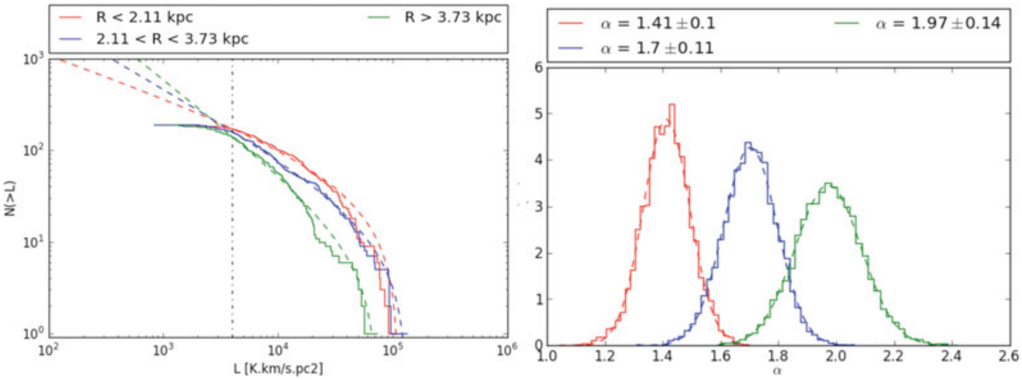

Figure 1. Cloud CO luminosity spectrum for different radial bins of M33 as indicated above the left panel. *Right*: uncertainties estimated via the bootstrapping method with 5000 trials for each radial bin. Uncertainties are indicated above the panel and clearly show how separate the distributions are.

uncertainties in the stellar initial mass function, and thus the measure of the SFR, and in the measure of the H_2 column density, this apparent constancy should be verified further. However, even if the SFR/M(H_2) ratio varies somewhat, it appears that the low level of SF in the outer parts of galaxies is due to the difficulty in forming molecular gas clouds rather than inefficient SF within molecular clouds.

Are the properties of molecular clouds in the outer disk different from the inner disk? Rosolowsky (2005) found that the Galactic cloud mass function steepened and Gratier *et al.* (2012) found that the cloud mass spectrum in M33 also steepened with increasing distance from the galactic center. This steepening with galactocenric distance of the mass function was confirmed in M 33 by the full cloud sample from the Druard *et al.* (2014) dataset, shown in Fig. 1, but also in M 51 by Colombo *et al.* (2014). It should be noted that in all these studies, the actual measurement is of the CO luminosity which is assumed proportional to the cloud mass.

These measurements imply that outer disk clouds are typically smaller than inner disk GMCs and thus high angular resolution is important to detect and study their properties. In M 33, unlike the Milky Way, no variation with galactocentric distance is found in the $N(H_2)/I_{CO}$ conversion factor (Gratier *et al.* subm.). Generally, in the M33 sample, outer disk clouds had significantly weaker CO emission and lower peak temperatures but also slightly narrower CO lines (Braine *et al.* in prep. and Gratier *et al.* (2012)). Despite the lower peak temperatures, the individual clouds that have been observed near or beyond R_{25} at high resolution still have CO brightness temperatures of typically 1K or more, making them readily detectable when pinpointed (Digel *et al.* 1994, Bigiel *et al.* 2010, Braine *et al.* 2012).

A total of 566 clouds were classified according to their level of star formation as shown and described in Fig. 2. Although the clouds are well-mixed in terms of galactocentric distance, the 'C' clouds are more CO-luminous than the 'A' and 'B' and the same steepening of the luminosity function is observed going from 'C' to 'A' as with increasing galactocentric distance (Fig. 2, bottom).

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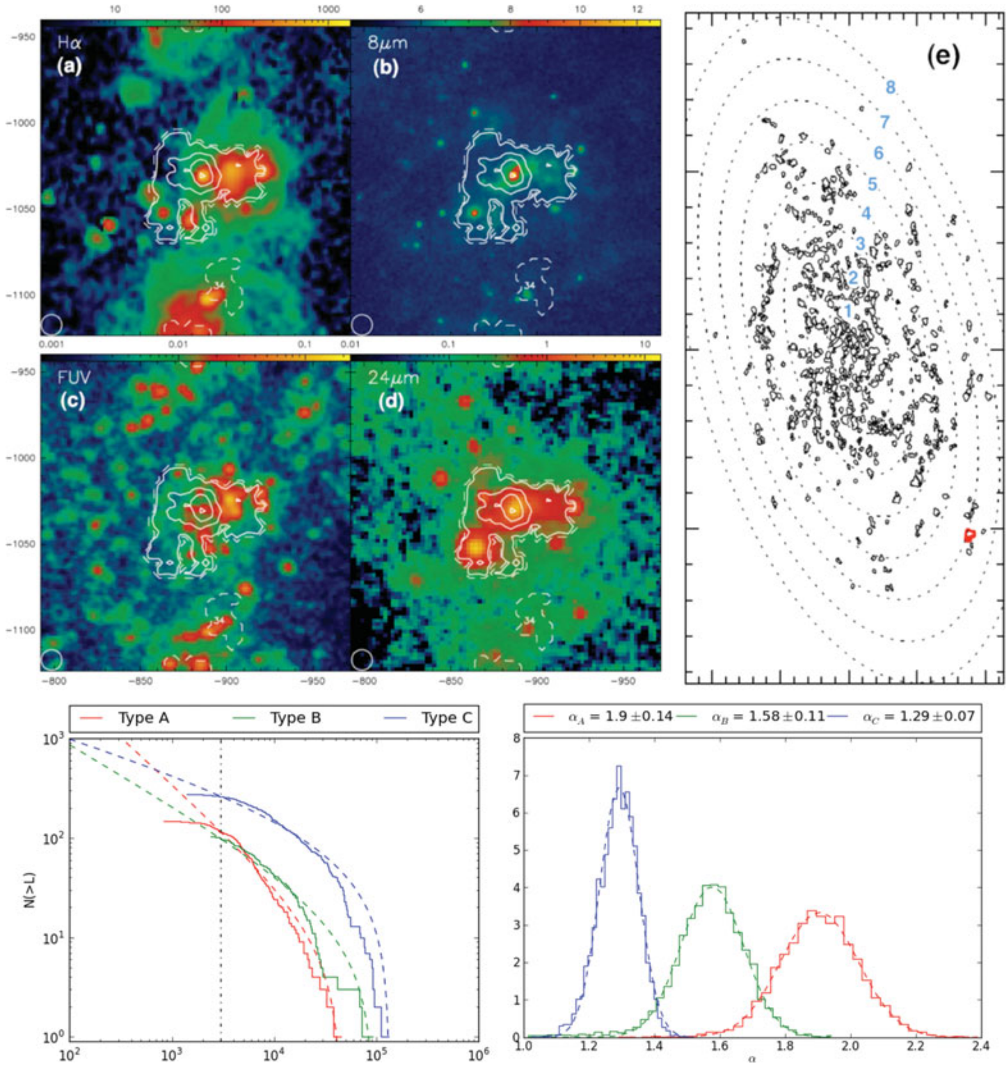

Figure 2. Illustration of method used to classify clouds as either without star formation (A), with embedded SF (B), or exposed SF (C). The wavebands were chosen to be affected or not by extinction and at higher angular resolution than the CO measurements. The rightmost panel (*e*) shows the distribution of molecular clouds in M 33 and the cloud shown in panels $a - d$ is highlighted in red. See Gratier *et al.* (2012) for further details. *Bottom panels*: Cloud CO luminosity spectrum for cloud types A, B, and C as in Fig. 1.

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