Dwarf Irregular Galaxies of the Local Group

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Abstract Local Group dwarf irregulars (dIrrs) cover an enormous range in star formation properties. Here I discuss these tiny galaxies as probes of star formation at the extremes of low gas densities and low metallicities. We have learned that 1) Star formation is inefficient in dIrrs and yet at very low $\Sigma_{\rm HI}$ (< 0.5 M$_\odot$ pc^{-2}) the star formation rate is higher than expected from a linear extrapolation from star formation at higher $\Sigma_{\rm HI}$. 2) Star formation correlates with existing stars and stellar feedback could be important. 3) Stellar disks go on for a long ways, often with very regular surface brightness profiles and reaching very low $\Sigma_{\rm HI}$. 4) Breaks in surface brightness profiles occur at about the same magnitude in both spirals and dwarfs, so something fundamental is taking place there. 5) Dwarf disks appear to grow from the "outside-in", contrary to spirals. 6) At low metallicity, star formation takes place in giant molecular clouds, but the photodissociation region is large.

1 Introduction

When I started graduate school, there were the "seven dwarfs" of the Local Group. Today of order 50 are known, and there are likely more to be found. Of these $\sim$20 are dwarf irregulars (dIrrs), lumpy little galaxies with gas. These are the dwarfs that are forming, or could potentially form, stars, and they are the subject of this discussion.

The Local Group contains dIrrs that span a large range of properties. One extreme is exemplified by Leo T (Figure 1), at a distance of 0.4 Mpc and a possible satellite of the Milky Way. It was discovered just recently (Irwin et al. 2007), and has an M_V of only -8, not much brighter than a large star cluster or even the kind of individual stars that my spouse (Phil Massey) works on. In fact it only has about 10^5

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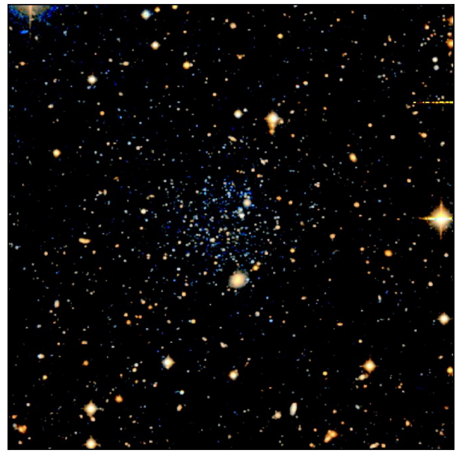

Fig. 1 Leo T from Irwin et al. (2007), by permission from M. J. Irwin.

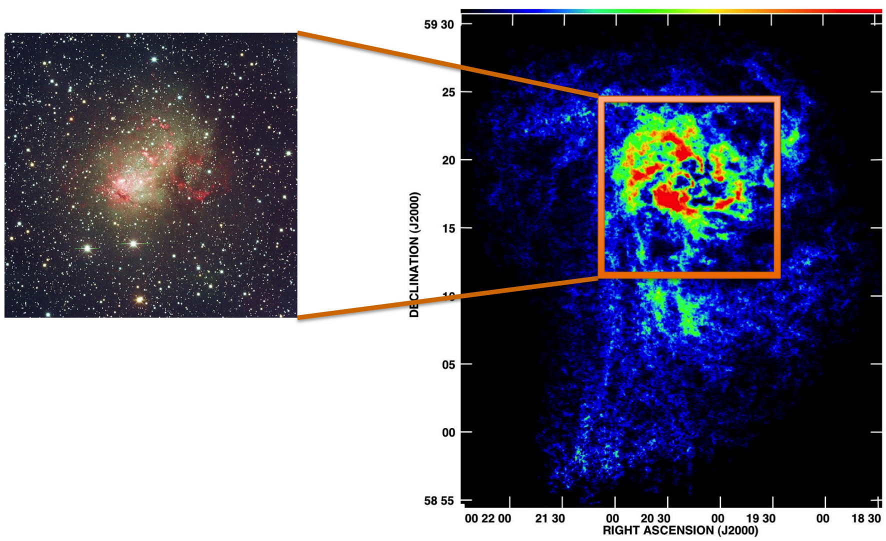

Fig. 2 IC 10 from Hunter et al. (2012). An optical image is on the left and false-color integrated HI on the right.

$M_\odot$ of stars and about 3 times that in HI (Ryan-Weber et al. 2008). The peak HI column density is a mere 7×10^{20} cm^{-2} and the gas is stable against gravitational instabilities. Nevertheless, the galaxy not only has old (>5 Gyr) stars, but young (200 Myr -1 Gyr) stars as well (de Jong et al. 2008). How could such a little puddle of gas form stars?

At the other extreme is IC 10 (Figure 2), at 0.7 Mpc, a satellite of M31, and an M_V of -16. It is the only starburst galaxy in the Local Group. In fact, it hosts an extraordinary surface density of short-lived evolved massive WR stars, stars (Massey & Holmes 2002), indicating a temporal coherence in the starburst across the galaxy.

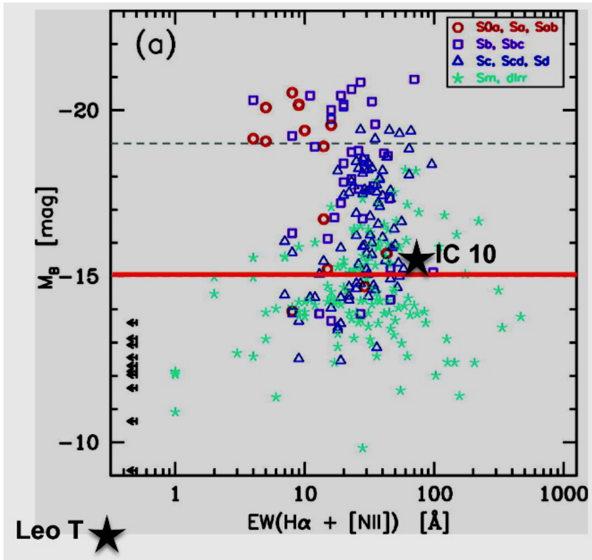

Fig. 3 Integrated Hα equivalent width, a measure of the ratio of new stars to old stars, plotted against M_B from Lee et al. (2007) by permission from J. Lee. IC 10 and Leo T are placed on this figure as large stars, using data from Kennicutt et al. (2008) for IC 10. Leo T actually has no current Hα emission, so it is placed at the low end of the logarithmic axis. The horizontal line at $M_B = -15$ marks the regime below which the EWs spread out to cover a larger range than above the line.

IC 10 contains $\sim 3 \times 10^7$ M$_\odot$ of HI gas with a peak column density of $\sim 10^{22}$ cm^{-2} (Wilcots & Miller 1998). The HI extends in a strange fan-like morphology to the south of the stellar disk, as well as to the east, and the kinematics are complex. Recently Nidever et al. (2013) discovered an HI filament stretching to a coherent gas blob and suggest that IC 10 may have merged with another dwarf.

Ricotti & Gnedin (2005) argue that Local Group dwarfs are defined by how they weathered the epoch of reionization in the early universe: “survivors” formed most of their stars after reionization, “true fossils” are those that became frozen in their pre-reionization state, and “polluted fossils” are those in between these two states. In their Figure 5, IC 10 is a survivor. Ricotti (2009) argues that Leo T is a dark matter minihalo that accreted gas after reionization, producing the bimodal stellar population seen in that galaxy. This would make Leo T a “polluted fossil.”

One thing we have learned about nearby dwarfs is that star formation rates become unstable in lower luminosity ($M_B > -15$) systems (Lee et al. 2007). Lee et al. plotted the integrated equivalent width of Hα, which is related to the ratio of new stars to old stars, against integrated galactic M_B. They find that giant spirals and brighter dwarfs occupy a narrow range of EWs, but lower luminosity systems cover a wide range. We show this plot in Figure 3 with IC 10 and Leo T placed on it. IC 10 lies just above the line denoting the $M_B = -15$ transition and Leo T, a long ways below. Lee et al. suggest a change in star formation regulation at low luminosities so that systems swing from higher rates to lower rates, called “gasping” star formation

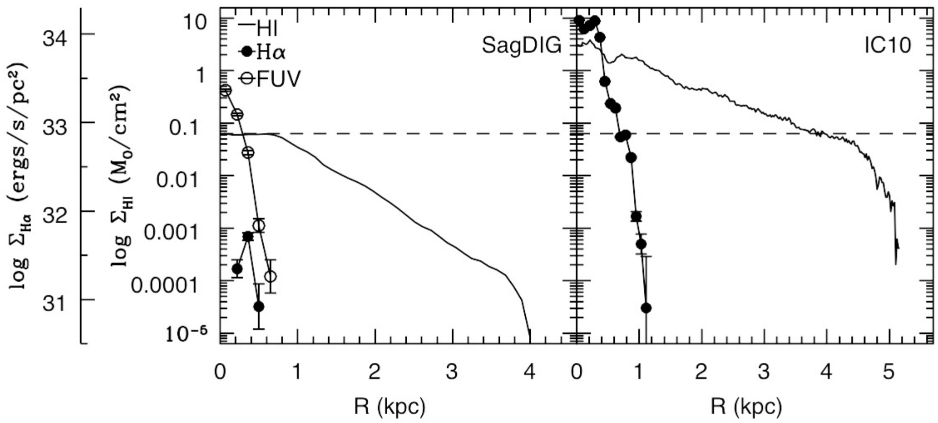

Fig. 4 HI surface density profiles from Hunter et al. (2012). The horizontal dashed line marks the highest surface densities in SagDIG to allow comparison with IC 10. The radial profiles for Hα emission and FUV (which is not available for IC 10) are also shown; both are measures of recent star formation. We see that, at the surface densities where star formation is taking place in SagDIG, in IC 10 there is no star formation. This illustrates the problem in connecting HI and star formation.

by Marconi et al. (1995) and collaborators. There is a hint that lower luminosity dwarfs also become puffier in shape (Zhang et al. 2012, Johnson et al. 2014), and perhaps the shape goes hand in hand with a global regulation instability.

Here I would like to discuss Local Group dIrrs as probes of star formation at the extremes of low gas densities and low metallicities. Low gas densities are relevant to understanding star formation in outer stellar disks. In addition, dIrrs give us a glimpse into star formation processes under HI-dominated, very low metallicity conditions, such as expected in proto-galaxies at high z.

2 Star formation at low gas densities

In the general picture of star formation, stars form from molecular clouds and molecular clouds form from atomic gas. Figure 4 illustrates the problem with understanding the connection between HI and star formation. Here I compare the HI surface density profile of IC 10 with that of SagDIG. SagDIG is a low star formation rate system and IC 10 is the starburst we discussed previously. The radial profiles of recent star formation tracers (Hα and FUV emission) are also shown. We see that at the radius in IC 10 ($\sim$4 kpc) where its $\Sigma_{\rm HI}$ drops to the value where all of the star formation is taking place in SagDIG ($\sim$0.1 $M_\odot$ pc^{-2}), there is no star formation. In IC 10 all of the star formation is taking place only at much higher $\Sigma_{\rm HI}$ ($\sim$a few $M_\odot$ pc^{-2}). Why?

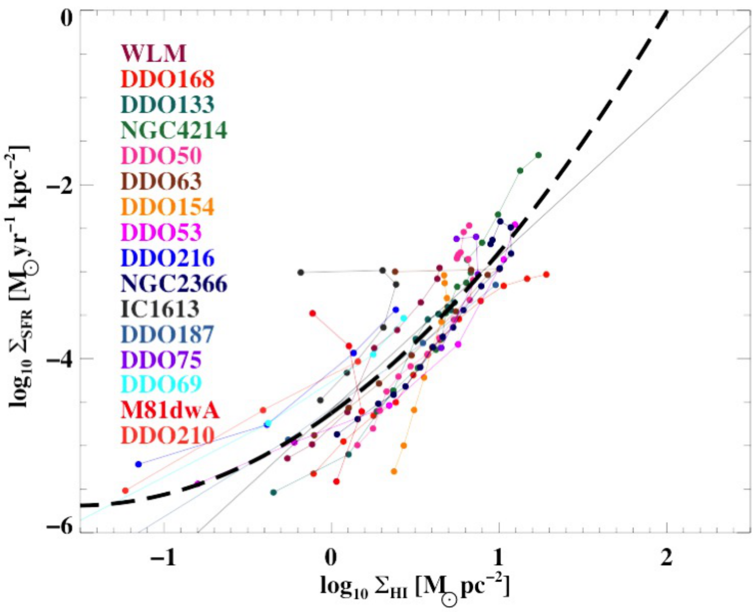

Fig. 5 Radial profiles of $\Sigma_{\rm SFR}$ versus $\Sigma_{\rm HI}$ for 20 dIrr galaxies examined in 400-pc cells (Ficut-Vicas et al. 2014, reproduced with permission of D. Ficut-Vicas.). The straight gray line is a linear fit to the profiles; the curved dashed black line is a polynomial fit. The star formation rate is higher at low $\Sigma_{\rm HI}$ than predicted by the relationship at higher $\Sigma_{\rm HI}$.

2.1 Empirical star formation properties

With the lack of a true understanding of the large-scale drivers of star formation, people have turned to empirical laws relating the atomic gas to recent star formation. Bigiel et al. (2008, 2010) divided a sample of mostly spiral galaxies into sub-kpc cells and Ficut-Vicas et al. (2014) similarly divided a sample of 20 dwarfs into 400 pc cells. They plot the star formation rate per unit area versus the HI gas density $\Sigma_{\rm HI}$ in each cell. For the inner disks of spirals, there is a pretty good relationship: the higher the HI gas density, the higher the star formation rate, until most of the HI turns molecular above 10 $M_\odot$ pc^{-2}. For dwarf galaxies and the outer disks of spirals there is also a general relationship but with a much higher (up to a factor of 100) spread of star formation rates for a given gas density. In general, too, the star formation efficiency, defined as the star formation per unit gas mass, is much lower in dwarfs than in spirals (Leroy et al. 2008, Ficut-Vicas et al. 2014).

However, there is something very peculiar that happens at the low end of $\Sigma_{\rm HI}$ (< 0.5 $M_\odot$ pc^{-2}) in dwarfs. Ficut-Vicas et al. (2014) find that the actual star formation rate there is higher than predicted from a linear extrapolation from higher $\Sigma_{\rm HI}$ regions. This is shown in Figure 5. What is driving star formation at very low gas densities?

Ficut-Vicas et al.'s (2014) study of dwarfs also shows that there is a strong correlation between star formation rate and the mass surface density of older stars. Are environmental conditions deterministic so that a given place in a galaxy always has the same star formation rate averaged over an appropriately long timescale? If so, then we don't know what the important environmental conditions are. Are stellar disk potentials important in determining star formation capability? But dIrrs are HI-dominated galaxies. Or is feedback from star formation crucial in dwarf galaxies that have nothing much else going for them to form star-forming gas clouds?

We know that star-induced star formation takes place. A beautiful example is Constellation III in the LMC (Dopita et al. 1985) where a star-forming event 15 Myr ago blew a hole in the HI 2 kpc across. The second generation of star formation is now taking place in the shell that surrounds the hole. But one of the consequences of this process is that sometimes the interstellar medium (ISM) of dwarfs ends up looking like Swiss cheeese - full of holes. This is especially true of dwarfs where limited shear means holes last a long time. This raises the questions: What percentage of star formation is due to stellar feedback? And, what is the effect of porosity (the filling factor of the holes) on star formation?

In the LMC, Dawson et al. (2013) have looked at the overall percentage of secondary star formation caused by supergiant shells, of which the LMC has many. They find 4-11% of the star formation today is due to stellar feedback. This is a lower limit since there are smaller shells that they did not include. In DDO 50, on the other hand, "most" of the star formation is associated with shells around holes (Stewart et al. 2000, Stewart & Walter 2000). Pohkrel et al. (2014) are currently in the process of addressing the two questions posed above for a large sample of dwarf galaxies spanning a wide range of properties.

There is another, less direct, potential connection between stars and star formation. This comes from the model of Ostriker et al. (2010). In this model ISM heating by stellar UV light plays a key role in regulating $\Sigma_{\rm SFR}$. It looks like there is a general correspondence between $\Sigma_{\rm SFR}$ and $\Sigma_{\rm stars}$ (compare, for example, their Figure 4, panels c and d). However, in gas-dominated regions like dIrrs, $\Sigma_{\rm SFR} \propto \Sigma_{\rm gas} \times \sqrt{\rho_{\rm stars} + \rho_{DM}}$, so $\log \Sigma_{\rm SFR} \propto \log \Sigma_{\rm stars}$, as observed, isn't obvious.

2.2 Outer Disks

Dwarf outer disks are the realm of *very* low gas densities. Nevertheless, stellar disks can extend an extraordinarily long ways. Through star counts, Saha et al. (2010) have traced a disk of old stars in the LMC to 12 disk scale lengths, an equivalent μ_I of 34 mag arcsec^{-2}. The young stars were traced to 8 disk scale lengths. Furthermore, the surface density of stars is exponential in form all the way in spite of the LMC being a very irregular galaxy. In DDO 70 and DDO 75 Bellazzini et al. (2014) have traced star counts to an equivalent μ_V of 31 mag arcsec^{-2}, about 6 disk scale lengths. Ultra-deep V-band and *GALEX* FUV imaging of 5 dwarfs revealed stellar disks with young stars to μ_V of 31 mag arcsec^{-2}, traced into the realm of highly stable gas (Hunter et al. 2011).

The Ostriker et al. (2010) model, which built on Elmegreen & Parravano (1994), may provide a way to understand stellar disks that go on and on into highly subcritical gas densities. In their model star formation adjusts to provide the needed FUV heating to balance cooling and, thus, to match the thermal pressure to the mid plane pressure set by the vertical gravitational field. So, the star formation rate continues, although declining with decreasing efficiency, to large radii, and there is no sharp cutoff caused by a $\Sigma_{\rm HI}$ limit. On the other hand, a comparison of the $\Sigma_{\rm SFR}$ predicted by the model with FUV surface photometry in a sample of dIrrs shows some correspondence between model and observations, but is not generally good.

Many of the dwarfs display broken stellar exponential profiles: an exponential surface density profile that changes slope in the outer disk with, usually, a downward bend. This break in the profiles implies a change in the cloud/star formation process at the break radius. Amazingly, however, this break occurs at about the same V-band surface brightness in spirals and in dwarfs (Herrmann et al. 2013). Clearly, something fundamental happens at the break in *both* spirals and dwarfs, but what?

Elmegreen & Hunter (2006) have proposed that the profile breaks represent a shift from gravitational instabilities driving cloud formation in the inner disk to turbulence compression in the outer disk. Turbulence adds nothing to star formation in the inner disk, but is, according to this model, crucial to the formation of clouds in the outer, stable gas disk. This model predicts the average break radius for dwarfs and that the break occurs closer to the center of the galaxy compared to spirals.

In some galaxies the outer disk surface brightness profiles are much more complex than a simple exponential with a break. In DDO 75, for example, the profile is flat to almost 1 kpc radius, then drops exponentially to 1.4 kpc. From there it drops less steeply to 2.6 kpc, brightens for a ways and then brightens some more to 4.4 kpc (Bellazzini et al. 2014). Bellazzini et al. suggest that DDO 75 has been disturbed. Ironically, DDO 75, being on the outer edge of the Local Group, had been thought to be one of the most pristine nearby dwarfs (Wilcots & Hunter 2002).

2.3 Outside-In Disk Growth

The current paradigm for spiral galaxies is that the stellar disks grow from the inside-out (see, for example, Muñoz-Mateos et al. 2007). However, for dwarfs disk growth appears to be from the outside-in. In a study of a 34 nearby dIrrs, Zhang et al. (2012) found that in systems with baryonic masses $< 10^8$ M$_\odot$ the star formation rate in the outer disk has been declining with time, while in the more massive dwarfs the radial ratios of star formation rates over different time scales is relatively flat. However, in the LMC, which is a massive dIrr, Meschin et al. (2013) also found outside-in disk growth from a study of star formation histories in 3 fields from 3.5 to 6 kpc radius. In the inner regions stars formed 7 Gyr ago and 4 Gyr ago in equal amounts and star formation is continuing today. However, in the outer field, stars

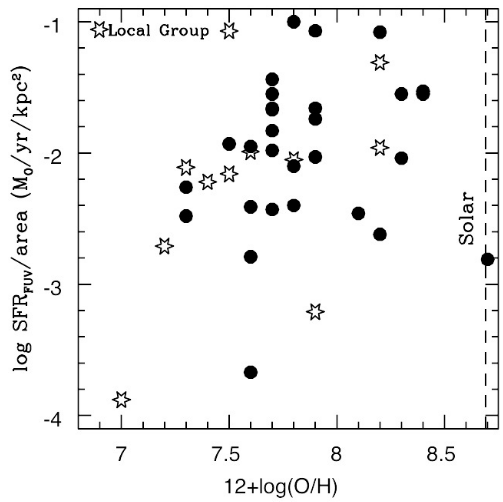

Fig. 6 Star formation rate per unit area versus oxygen abundance for a sample of 40 dIrrs, including 11 Local Group dwarfs (Hunter et al. 2012). The dwarfs shown here range from 1/2 solar to 1/50 solar metallicity.

formed 7 Gyr ago, only 40% more formed 4 Gyr ago, and star formation ceased about 1 Gyr ago. One possibilty is that gas is somehow being removed from outer disks of dwarfs making it increasingly difficult to form stars out there.

3 Star formation at low metallicity

Atoms heavier than H and He and dust play an important role in cooling the gas so that it can make cold molecular clouds, where we typically find star formation. Figure 6 shows a plot of star formation rate per unit area versus $12+\log(O/H)$ for a sample of 40 dIrr galaxies that contains 11 of the Local Group dIrrs. The oxygen abundances range from 1/2 solar to 1/50 solar in this sample, and are illustrative of the range of metallicities of Local Group dIrrs.

One of the results of low metallicity is poor shielding of molecular clouds. As a consequence it is expected that the structure of the molecular cloud itself will change as the metallicity drops. In particular the CO core will shrink and the photodissociation region (PDR) will grow (Maloney & Black 1988, Bolatto et al. 1999, Röllig et al. 2006). In fact, it is possible that in galaxies with metallicities below a few percent of solar, star formation will proceed in the cold atomic gas rather than in molecular gas (Krumholz 2012).

The shrinking CO core with declining metallicity has meant that molecular gas has been hard to detect at metallicities below 20% of solar. However, Elmegreen et al. (2013) used the APEX sub-mm telescope in Chile to observe CO (3-2) in WLM with a beam that is 87 pc at WLM. They detected two molecular clouds with H_2 masses of 1-2$\times10^5$ $M_\odot$. Thus, at 13% of solar metallicity, star formation is taking

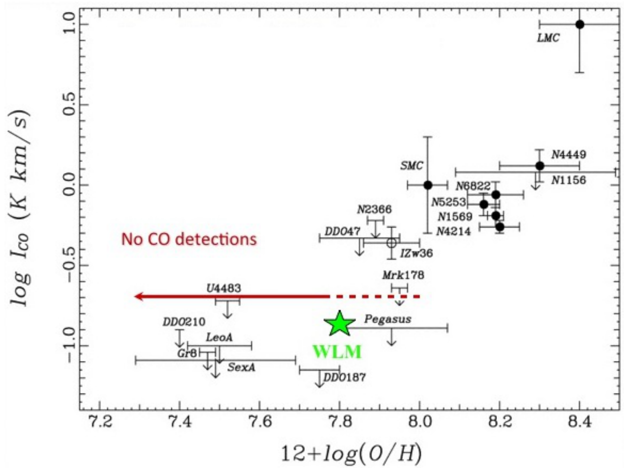

Fig. 7 Measurements of I_{CO} as a function of galaxy oxygen abundance at low metallicity. Measurements from Tacconi & Young (1987) and Taylor et al. (1988); plot courtesy of M. Rubio. Only the solid black circles and the green star marking WLM are detections. The measurement of CO in WLM extends the detections to 13% of solar metallicity (Elmegreen et al. 2013).

place in giant molecular clouds. Figure 7 shows the WLM detection in the context of other measurements as a function of oxygen abundance.

With the WLM CO detection we can now begin to test the model of shrinking CO core and growing PDR with decreasing metallicity. In Figure 8, contours of a *Herschel* image of the [CII]λ158 μm fine-structure line of one region shows the PDR (Cigan et al. 2014). The white circle shows the CO detection. An ALMA CO (1-0) map that is currently pending will further resolve the CO core, but Cigan et al. can already show that the CO core is $<$ 86 pc diameter and the PDR is an annulus around the core with a thickness that is comparable to the core diameter. Additional CO observations with the ALMA sub-mm array of other dIrrs in the Local Group at even lower metallicity may finally allow us to construct a picture of molecular cloud structure as a function of metallicity.

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References

1. Bigiel, F., et al., 2008, AJ, 136, 2846
2. Bigiel, F., et al., 2010, AJ, 140, 1194
3. Bellzzzini, M., et al., 2014, A&A, in press
4. Bolatto, A. D., et al., 1999, ApJ, 513, 275
5. Cigan, P., et al., 2014, in preparation

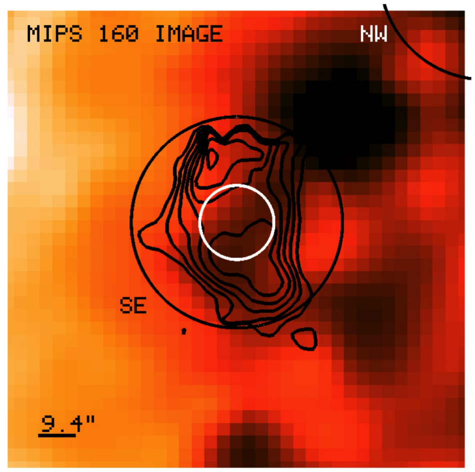

Fig. 8 *Spitzer* MIPS 160 μm image of a region where CO (3-2) was detected in WLM (Elmegreen et al. 2013). The white circle is the telescope beam size and pointing that produced the detection. The black contours are of [CII]λ158 μm, the primary fine-structure line of the PDR (Cigan et al. 2014). The large black circle is the field of view of pending ALMA CO (1-0) observations. These data reveal a PDR that is at least comparable in width to the diameter of the CO core at a metallicity 13% of solar (Cigan et al. 2014).

6. Dawson, J. R., et al., 2013, ApJ, 763, 56
7. de Jong, J. T. A., et al. 2008, ApJ, 680, 1112
8. Dopita, M. A., et al., 1985, ApJ, 297, 599
9. Elmegreen, B. G., & Hunter, D. A., 2006, ApJ, 636, 712
10. Elmegreen, B. G., & Parravano, A. 1994, ApJ, 435, L121
11. Elmegreen, B. G., et al., 2013, Nature, 495, 487
12. Ficut-Vicas, D., et al., 2014, in preparation
13. Herrmann, K. A., Hunter, D. A., & Elmegreen, B. G., 2013, AJ, 146, 104
14. Hunter, D. A., et al., 2011, AJ, 142, 121
15. Hunter, D. A., et al., 2012, AJ, 144, 134
16. Irwin, V., et al., 2007, ApJ, 656, L13
17. Johnson, M., et al., 2014, in preparation
18. Kennicutt, R. C., Jr., et al., 2008, ApJS, 178, 247
19. Krumholz, M. R., 2012, ApJ, 759, 9
20. Lee, J. C., et al., 2007, Ap, 671, L113
21. Leroy, A., et al., 2008, AJ, 136, 2782
22. Maloney, P., & Black, J. H., 1988, ApJ, 325, 389
23. Marconi, G., et al., 1995, AJ, 109, 173
24. Massey, P., & Holmes, S., 2002, ApJ, 580, 35
25. Muñoz-Mateos, J. C., et al., 2007, ApJ, 658, 1006
26. Nidever, D. L., et al., 2013, ApJ, 779, L15
27. Ostriker, E., et al., 2010, ApJ, 721, 975
28. Ricotti, M., 2009, MNRAS, 392, L45
29. Ricotti, M., & Gnedin, N. Y., 2005, ApJ, 629, 259
30. Röllig, M., et al., 2006, A&A, 451, 917
31. Ryan-Weber, E. V., et al., 2008, MNRAS, 384, 535
32. Saha, A., et al., 2010, AJ, 140, 1719
33. Stewart, S. G., & Walter, F., 2000, AJ, 120, 1794
34. Stewart, S. G., et al., 2000, ApJ, 529, 201
35. Tacconi, L, & Young, J. S., 1987, ApJ, 322, 681
36. Taylor, C. L., et al., 1998, AJ, 116, 2746
37. Wilcots, E. M., & Hunter, D. A., 2002, AJ, 123, 1476
38. Wilcots, E. M., & Miller, B. W., 1998, AJ, 116, 2363
39. Zhang, H.-X., et al., 2012, AJ, 143, 47