Phases of the ISM as seen by LITTLE THINGS

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Date: 1st August 2013
Content

• Brief overview of LITTLE THINGS

• Breaking the metallicity barrier: CO in the dIrr galaxy WLM
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• Breaking the metallicity barrier: CO in the dIrr galaxy WLM
LITTLE THINGS provides observations of the neutral, atomic gas phase with the Karl G. Jansky VLA, the reservoir of the fuel for star formation.
The Team

Deidre Hunter (PI, Lowell Observatory)
Elias Brinks (Univ of Hertfordshire, UK)
Bruce Elmegreen (IBM T. J. Watson Research Center)
Michael Rupen (NRAO)
Caroline Simpson (Florida International Univ)
Fabian Walter (MPIA, Germany)
David Westpfahl (New Mexico Tech)
Lisa Young (New Mexico Tech)
Trisha Ashley (pre-doc, FIU)
Phil Cigan (pre-doc, New Mexico Tech)
Dana Ficut-Vicas (pre-doc, Univ Hertfordshire)
Ged Kitchener (pre-doc, Univ Hertfordshire)
Volker Heesen (post-doc, Univ Southampton)
Kim Herrmann (Penn State – Mont Alto)
Megan Jackson (post-doc NRAO)
Se-Heon Oh (Univ Western Australia)
Andreas Schruba (CalTech)
Hongxin Zhang (Peking Univ)
The Sample

The larger sample was selected to have gas, so targets could form stars in principle, and not be obviously interacting as we are interested in internal triggering processes (Hunter & Elmegreen 2004, 2006).

The LITTLE THINGS sub-sample, 42 targets, covers the range of properties of the larger survey; it is representative and includes the extremes.

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IC 1613

HI on optical/UV

V$_{hel}$

HI

σ
DDO 50 metadata

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- $UBV$ images
  - FITS files: $U, B, V$
  - Calibration parameters
  - Further information: Hunter & Elmegreen 2006
- $JHK$ images: None
- Halpha images
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    - Halpha (with stars)
    - Halpha (minus stellar continuum and sky)
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  - Further information: Hunter & Elmegreen 2004
- Ultraviolet images
  - FITS files: FUV, NUV
  - Further information: Hunter, Elmegreen, & Ludka 2010, Zhang et al. (2011)
- Spitzer IRAC images
  - FITS files: LVL IRAC Data
  - Further information: Hunter, Elmegreen, & Martin 2006

https://science.nrao.edu/science/surveys/littlethings/
DDO 50 metadata

NEW: 6cm radio continuum survey

DDO 50 metadata

- VLA HI: Observations
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- Spitzer IRAC images
  - FITS files: LVL IRAC Data
  - Further information: Hunter, Elmegreen, & Martin 2006

https://science.nrao.edu/science/surveys/littlethings/
The other three dashed lines in the top row represent constant y r, 100 Gyr and 1000 Gyr. All points are in radial bins of a beam size and their coloured cores represent 10%, 25%, 50%, 75% and 90% of the pixel by pixel distribution.

Figure 4.21: For all galaxies in our subsample observed in FU

CHAPTER 4

SK-plots for some of the LT dwarfs: SFR density versus HI surface density. Coloured symbols are radial averages. Cell size: 400 pc.
X-factor - metallicity relation

Carbon monoxide (CO) is the primary tracer for interstellar clouds where stars form, but it has never been detected in galaxies in which the oxygen abundance relative to hydrogen is less than 20 per cent of that of the Sun, even though such low-metallicity galaxies often form stars. This raises the question of whether stars can form in dense gas without molecules, cooling to the required near-zero temperatures by atomic transitions and dust radiation rather than by molecular line emission; and it highlights uncertainties about star formation in the early Universe, when the metallicity was generally low. Here we report the detection of CO in two regions of a local dwarf irregular galaxy, WLM, where the metallicity is 13 per cent of the solar value. We use new submillimetre observations and archival far-infrared observations to estimate the cloud masses, which are both slightly greater than 100,000 solar masses. The clouds have produced stars at a rate per molecule equal to 10 per cent of that in the local Orion nebula cloud. The CO fraction of the molecular gas is also low, about 3 per cent of the Milky Way value. These results suggest that in small galaxies both star-forming cores and CO molecules become increasingly rare in molecular hydrogen clouds as the metallicity decreases.

Wolf-Lundmark-Melotte (WLM) is an isolated dwarf galaxy at the edge of the Local Group. It has a low star-formation rate because of its small size and, like other dwarf irregular (dIrr) galaxies, shows no previous evidence for the molecular gas that always accompanies young stars in larger galaxies. One problem with the detection of molecules in such gas is CO, and dIrr galaxies have low carbon and oxygen abundances relative to hydrogen. No galaxy with an OH abundance less than 20% has been detected using CO as a tracer. Far more abundant is molecular hydrogen (H$_2$), but this does not have an observable state of excitation at the low temperatures ($\sim$10–30 K) required for star formation.

To search for star-forming gas, we surveyed WLM for CO (J = 3 → 2) emission in rotational state J and for continuum dust emission at 345 GHz using the Atacama Pathfinder Experiment (APEX) telescope at Llano de Chajnantor, Chile, with the Swedish Infrared Facility Instrument (LABOCA). We also used a map of dust emission at 160 μm from the Spitzer Large Volume Legacy Survey and a map of atomic hydrogen re-reduced from the archives of the Jansky Very Large Array radio telescope. The dust measurements can be converted to a dust temperature and a dust mass, and, after applying a suitable gas-to-dust ratio, to a gas mass from which the H$_2$ mass can be subtracted to give the H$_2$ mass for comparison with CO.

Figure 1 shows WLM and the two regions, designated A and B, where we detected CO(J = 3 → 2) emission, along with H$_2$, far-infrared (FIR) and submillimetre images. Observed and derived parameters are listed in Tables 1 and 2, respectively. The peak CO brightness temperature in each detected region is ~0.01–0.015 K and the line width is ~12 km s$^{-1}$ (full-width at half-maximum). Previous attempts to detect CO(J = 1 → 0) in WLM partly overlapped region A with a 45′′ aperture and determined a 5σ upper limit to the CO(1 → 0) intensity of 0.18 K km s$^{-1}$. Our observation with an 18′′ beam aperture yields an intensity of 0.200 ± 0.046 K km s$^{-1}$ for CO(3 → 2) in the same region. The difference arises because the CO cloud is unresolved even by our 18′′ beam—we did not detect comparable CO(3 → 2) intensities in our searches adjacent to region A. The previous upper limit corresponds to a maximum CO(1 → 0) luminosity of 8.300 K km s$^{-1}$ pc$^2$ inside 45′′ (which corresponds to a beam diameter of 215 pc at WLM), whereas the cloud we detect has a CO(3 → 2) luminosity ~6.7 times smaller (1.500 K km s$^{-1}$ pc$^2$). Likewise, the previous null detection in CO(1 → 0] claimed a 5σ upper limit to the CO(1 → 0) intensity of ~0.46 K km s$^{-1}$, which is about the same as our CO(3 → 2) detection, but their closest pointing differed from region A by ~70 pc (14′′), or half the beam diameter for CO(1 → 0], which could have been enough to take it off the CO cloud.

The 160-μm, 870-μm and H$_2$ peaks are slightly offset from the CO positions, indicating variations in temperature and molecular fraction. A large H$_2$ and FIR cloud that surrounds region A, designated region A1, was used to measure the dust temperature, $T_d$ = 15 K, which was assumed to be the same throughout the region (the 160-μm observation does not resolve region A, and so a more localized temperature measurement is not possible). We determined $T_d$ from the 870-μm and 160-μm fluxes corrected for the CO(3 → 2) line and broadband free-free emission (Table 1), assuming a modified black-body function with dust emissivity proportional to frequency to the power $\beta$. Local measurements suggest that $\beta$ = 1.78 ± 0.08, although a range is possible depending on grain temperature and properties. The 870-μm flux was also corrected for an unexplained FIR and submillimetre excess that is commonly observed in other low-metallicity galaxies. An alternate...
Carbon monoxide (CO) is the primary tracer for interstellar clouds where stars form, but it has never been detected in galaxies in which the oxygen abundance relative to hydrogen is less than 20 per cent of that of the Sun, even though such ‘low-metallicity’ galaxies often form stars. This raises the question of whether stars can form in dense gas without molecules, cooling to the required near-zero temperatures by atomic transitions and dust radiation rather than by molecular line emission, and it highlights uncertainties about star formation in the early Universe, when the metallicity was generally low. Here we report the detection of CO in two regions of a local dwarf irregular galaxy, WLM, where the metallicity is 13 per cent of the solar value. We use new submillimetre observations and archival far-infrared observations to estimate the cloud masses, which are both smaller than 100,000 solar masses. The clouds have produced stars at a rate per molecule equal to 10 per cent of that in the local Orion nebula cloud. The CO fraction of the molecular gas is also low, about 3 per cent of the Milky Way value. These results suggest that in small galaxies both star-forming cores and CO molecules become increasingly rare in molecular hydrogen clouds as the metallicity decreases.

Wolf-Lundmark-Melotte (WLM) is an isolated dwarf galaxy at the edge of the Local Group. It has a low star-formation rate due to its small size and, like other dwarf irregular (dIr) galaxies, shows no previous evidence for molecular gas that always accompanies young stars in larger galaxies. One problem with the detection of molecules is that the dominant tracer of such gas is CO, and dIr galaxies have low carbon and oxygen abundances relative to hydrogen. No galaxy with an OH abundance less than 20 per cent has been detected using CO as a tracer. Far more abundant is molecular hydrogen (H2), but this does not have an observable state at excitation at the low temperatures (∼10–30 K) required for star formation. To search for star-forming gas, we surveyed WLM for CO(1-0) emission in rotational state J and for continuum dust emission at 345 GHz using the Atacama Pathfinder Experiment (APEX) telescope at Llano de Chajnantor, Chile, with the Swedish Infrared Facility Instrument (LABOCA). We also used a map of dust emission at 160 µm from the Spitzer Local Volume Legacy Survey and a map of atomic hydrogen re-reduced from the archives of the Jansky Very Large Array radio telescope. The dust measurements can be converted to a dust temperature and a dust mass, and, after applying a suitable gas-to-dust ratio, to a gas mass from which the H1 mass can be subtracted to give the H2 mass for comparison with CO.

Figure 1 shows WLM and the two regions, designated A and B, where we detected CO(3-2) emission, along with H1, far-infrared (FIR) and submillimetre images. Observed and derived parameters are listed in Tables 1 and 2, respectively. The peak CO brightness temperature in each detected region is t = 0.01-0.015 K and the line-width is 12 km s−1 (full-width at half-maximum). Previous efforts to detect CO(J = 1-0) in WLM partly overlapped region A with a 45 arcmin aperture and determined a 5σ upper limit to the CO(1-0) intensity of 0.18 K km s−1. Our observation with an 18 arcsec beam yields an intensity of 0.200 ± 0.046 K km s−1 for CO(3-2) in the same region. The difference arises because the CO cloud is unresolved even by our 18 arcsec beam—we did not detect comparable CO(3-2) intensities in our searches adjacent to region A. The previous upper limit corresponds to a maximum CO(1-0) luminosity of 8,300 K km s−1 pc−2 inside 45 arcsec (which corresponds to a beam diameter of 215 pc at WLM), whereas the cloud we detect has a CO(3-2) luminosity ~10 times smaller (1,500 K km s−1 pc−2). Likewise, the previous null detection in CO(J = 2-1) claimed a 5σ upper limit that is about the same as our CO(3-2) detection, but their closest pointing differed from region A by ~70 pc (14 arcsec), or half the beam diameter for CO(2-1), which could have been enough to take it off the CO cloud.

The CO(3-2), H1, and 160-µm peaks are slightly offset from the CO positions, indicating variations in temperature and molecular fraction. A large H1 and FIR cloud that surrounds region A, designated region A1, was used to measure the dust temperature, Td = 15 K, which was assumed to be the same throughout the region (the 160-µm observation does not resolve region A, and so a more localized temperature measurement is not possible). We determinedTd from the 870-µm and 160-µm fluxes corrected for the CO(3-2) line and broadband free-free emission (Table 1), assuming a modified black-body function with dust emissivity proportional to frequency to the power β. Local measurements suggest that β = 1.78 ± 0.08, although a range is possible depending on grain temperature and properties. The 870-µm flux was also corrected for an unexplained FIR and submillimetre excess that is commonly observed in other low-metallicity galaxies. An alternate
Carbon monoxide in clouds at low metallicity in the dwarf irregular galaxy WLM

Bruce G. Elmegreen1, Monica Rubio2, Deidre A. Hunter3, Celia Verdugo2, Elias Brinks4 & Andreas Schruba5

Carbon monoxide (CO) is the primary tracer for interstellar clouds where stars form, but it has never been detected in galaxies in which the oxygen abundance relative to hydrogen is less than 20 per cent of that of the Sun, even though such low-metallicity galaxies often form stars. This raises the question of whether stars can form in dense gas without molecules, cooling to the required near-zero temperatures by atomic transitions and dust radiation rather than by molecular line emission1; and it highlights uncertainties about star formation in the early Universe, when the metallicity was generally low. Here we report the detection of CO in two regions of a local dwarf irregular galaxy, WLM, where the metallicity is 13 per cent of the solar value2,3. We use new submillimetre observations and archival far-infrared observations to estimate the cloud masses, which are both slightly greater than 100,000 solar masses. The clouds have produced stars at a rate per molecule equal to 10 per cent of that in the local Orion nebula cloud. The CO fraction of the molecular gas is also low, about 3 per cent of the Milky Way value. These results suggest that in small galaxies both star-forming cores and CO molecules become increasingly rare in molecular hydrogen clouds as the metallicity decreases.

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To search for star-forming gas, we surveyed WLM for CO (J = 3–2) emission in rotational state J and for continuum dust emission at 345 GHz using the Atacama Pathfinder Experiment (APEX) telescope at Llano de Chajnantor, Chile, with the Swedish Heterodyne Facility Instrument11 and the Large APEX Bolometer Camera12 (LABOCA). We also used a map of dust emission at 160 μm from the Spitzer Large Volume Legacy Survey13 and a map of atomic hydrogen re-reduced from the archives of the Jansky Very Large Array radio telescope. The dust measurements can be converted to a dust temperature and a dust mass, and, after applying a suitable gas-to-dust ratio, to a gas mass from which the H2 mass can be subtracted to give the H2 mass for comparison with CO.

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Table 1: Observations of WLM

<table>
<thead>
<tr>
<th>Source</th>
<th>Region</th>
<th>Right ascension</th>
<th>Declination</th>
<th>Beam diameter (°)</th>
<th>Flux</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO3-2</td>
<td>A</td>
<td>0h 1m 57.32s</td>
<td>-15° 26' 49.5''</td>
<td>0.200 ± 0.046 K km s^-1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>A</td>
<td>0h 1m 57.32s</td>
<td>-15° 26' 49.5''</td>
<td>2.66 ± 0.03 mJy (0.11, 0.02)*</td>
<td></td>
</tr>
<tr>
<td></td>
<td>A</td>
<td>0h 1m 57.32s</td>
<td>-15° 26' 49.5''</td>
<td>4.10 ± 0.25 mJy</td>
<td></td>
</tr>
<tr>
<td></td>
<td>A</td>
<td>0h 1m 57.32s</td>
<td>-15° 26' 49.5''</td>
<td>15.2 ± 0.1 mJy (0.01, 0.005)*</td>
<td></td>
</tr>
<tr>
<td></td>
<td>A</td>
<td>0h 1m 57.32s</td>
<td>-15° 26' 49.5''</td>
<td>136.2 ± 1.6 mJy (0.05)*</td>
<td></td>
</tr>
<tr>
<td></td>
<td>A</td>
<td>0h 1m 57.32s</td>
<td>-15° 26' 49.5''</td>
<td>0.129 ± 0.024 K km s^-1</td>
<td></td>
</tr>
</tbody>
</table>

*Quantities in parentheses are the CO(3–2) flux and the free-free emission, both in mJy, that were subtracted from the source flux before calculating the dust flux. The CO(3–2) flux is given in mJy, which was subtracted from the source flux before calculating the free-free flux. The average FIR excess factor for the Small Magellanic Cloud (SMC) is 1.7, so we divide the CO-corrected and free-free-corrected 870-μm fluxes in the table by 1.7 to get the thermal dust flux.
GMC as function of Z

Changing structure of a GMC as metallicity decreases: ISM\(^+\) (yellow) and PDR (grey) increase while CO (dark grey) decreases. As dust decreases, \(A_V \sim 1\) moves deeper into the GMC.

CO disappears \(A_V \lesssim 2\); \(H_2\) can exist at lower \(A_V\).
ISM at low metallicity

- low metallicity $\rightarrow$ low dust content (GDR $\propto Z^{-1}$)
- PAH emission down
- $T_{\text{dust}}$ increases ($\sim 32$ K in dIrr versus 20-25 K for spirals)
- excess sub-mm emission beyond 500 $\mu$m (cold dust reservoir?)
- [CII] 158 $\mu$m/CO increases
- $\alpha_{\text{CO}}$ increases steeply with decreasing metallicity
X-factor(Z) and DGR(Z)

\[ \alpha_{\text{CO}} \text{ increases non-linearly with decreasing metallicity} \]

\[ \text{GDR increases linearly with decreasing metallicity} \]


see also Sandstrom et al. 2012, arXiv1212.1208
**WLM: Wolf-Lundmark-Melotte**

- $D = 985 \pm 33$ kpc
- $M_* = 1.6 \times 10^7$ M$_\odot$
- $M_{\text{HI}} = 7.1 \times 10^7$ M$_\odot$
- $V_{\text{rot}} = \sim 36$ km s$^{-1}$
- $12 + \log(O/H) = 7.8$ (SMC: 8.0)
- SFR = $0.006$ M$_\odot$ yr$^{-1}$
- $sSFR$ (WLM) = $12 \times sSFR(MW)$
APEX CO(J=3-2) detection

CO (J=3-2) detected at two locations in WLM

18” beam

5σ detections

velocity agrees with HI

Elmegreen et al. 2013, Nature, 495, 487
LABOCA cold dust in WLM

Also, cold dust detected near region A, at 870 μm with LABOCA on APEX

LABOCA detection coincides with Spitzer 160 μm
APEX CO($J=3-2$) detection

Molecular cloud shell, Observed with Herschel

Image: Warm dust

CO detection
Herschel PACS [CII] in WLM
Herschel PACS [CII] in WLM

See Poster by Phil Cigan
GMCs in WLM

* use the MIPS and LABOCA to calculate the dust mass

* convert the dust mass to a total (HI+H\textsubscript{2}) gas mass; we assume that the DGR continues to scale linearly with metallicity, so GDR = 1100 (assumed; MW value of \(~145\) scaled by \([\text{O/H}]\))

* subtract the observed HI mass; this leaves the H\textsubscript{2} mass

* GMC mass: \(1.8 \pm 0.8 \times 10^5 \text{ M}_\odot\) and \(1.2 \pm 0.6 \times 10^5 \text{ M}_\odot\)

* this leads to a mass conversion factor \(\alpha_{\text{CO}} = 124 \pm 60 \text{ M}_\odot \text{ pc}^{-2} / (\text{K km s}^{-1})\) or \(~30 \times \text{MW value}) (\(X_{\text{CO}}\)-factor: \(5.8 \pm 2.8 \times 10^{21} \text{ cm}^{-2} / (\text{K km s}^{-1})\))
Conversion factor versus metallicity

\[
\alpha_{\text{CO}} \cdot 10^{-1} = \tau_{\text{dep}} \frac{\text{SFR}}{L_{\text{CO}}} \left[ M_\odot \text{pc}^{-2} (\text{K km s}^{-1})^{-1} \right]
\]

Different Methods:
- GMC Modelling: Bolatto+08
- Dust Modelling: Leroy+11
- SFR Scaling: Genzel+11 (z\geq1)
  - This Work (z=0)

Draine et al. (2007)

Milky Way

Summary

• LITTLE THINGS is in great shape...watch this space!

• We broke in WLM ($12 + \log(O/H) = 7.8$) the low-metallicity limit for a CO detection

• $\alpha_{CO} = 124 \pm 60 \, M_\odot \, pc^{-2} / (K \, km \, s^{-1})$ or $\sim 30 \times$ MW value

• GDR = 1100 (assumed; MW value scaled by [O/H])

• GMC mass: $1.8 \pm 0.8 \times 10^5 \, M_\odot$ and $1.2 \pm 0.6 \times 10^5 \, M_\odot$

• SFR per molecule in WLM $\sim$ SFR in MW (SFE $\sim$ 1.5 - 6.7 Gyr)
The End