A high resolution study of the star-formation law: the case of M33

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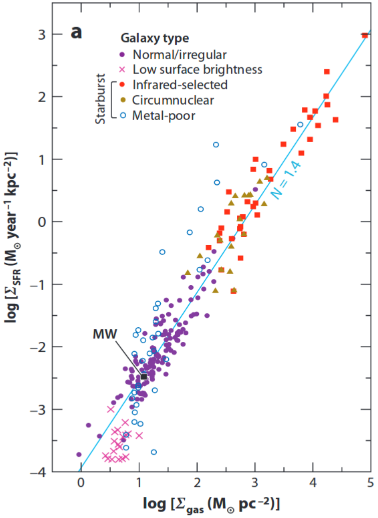
Introduction

- Relationship between surface density of star formation and gas (Schmidt, 1959):

$$\Sigma_{SFR} \propto \Sigma_{\rm gas}^{N} \qquad (1)$$

- Kennicutt (1998) found $N \simeq 1.4$ for 100 nearby galaxies



Introduction

Physical nature of this law?

- Gravitational collapse (Elmegreen 1994; Krumholz & Thompson 2007) – $N = 1.5$
- SFR dictated by amount of dense gas (Lada+, 2012), $N = 1$ – found for nearby spirals by Bigiel+ (2008)

Introduction

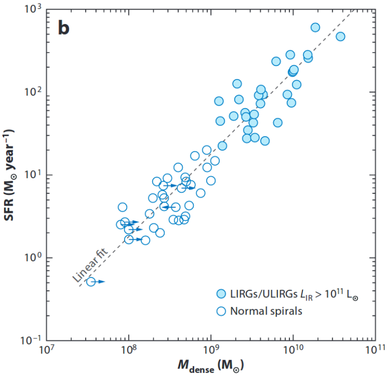
Higher resolution studies...

- Molecular gas, rather than total gas drives SF? (Bigiel+, 2008)
- Breaks down at scale of a giant molecular cloud (GMC) complex (Onodera+, 2010; Boquien+, 2015)

Alternatives

Dense gas?

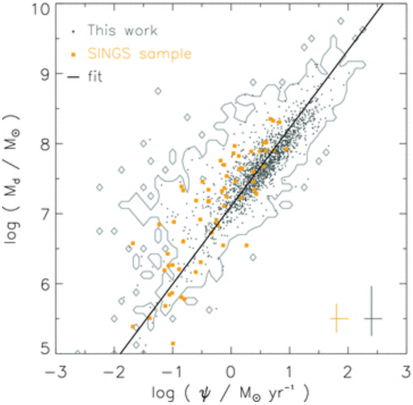
- Stars condense out of dense gas in GMCs (André+, 2010, Lada+, 2010)
- Expect a linear relationship between dense gas mass and SFR (Gao & Solomon, 2004)



Alternatives

Dust?

- Tight relationship between dust mass and SFR (da Cunha+, 2010)
- An evolutionary sequence?



What we want to do

- High resolution study of SF law
- Use a variety of SF and gas tracers
- Does the law break down for scales $\sim$ 100pc?
- Is the relationship driven by gravity or dense gas?
- If it does break down, do other relationships hold?

M33

- $\sim$ 840 kpc away (Madore & Freedman, 1991)
- Inclination $\sim 56^\circ$ (Regan & Vogel, 1994)
- Half-solar metallicity (Rosolowsky & Simon, 2010)
- Relatively unperturbed, despite a tidal encounter with M31 (McConnachie+, 2010)

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- Pretty!

SFR Data

- 3 tracers of SFR: 24μm+FUV, TIR luminosity, MAGPHYS
- For these (especially MAGPHYS), we need to cover the entire spectrum, UV to sub-mm
- Use archival data, with some new SCUBA-2 data complementing the sub-mm

Data used

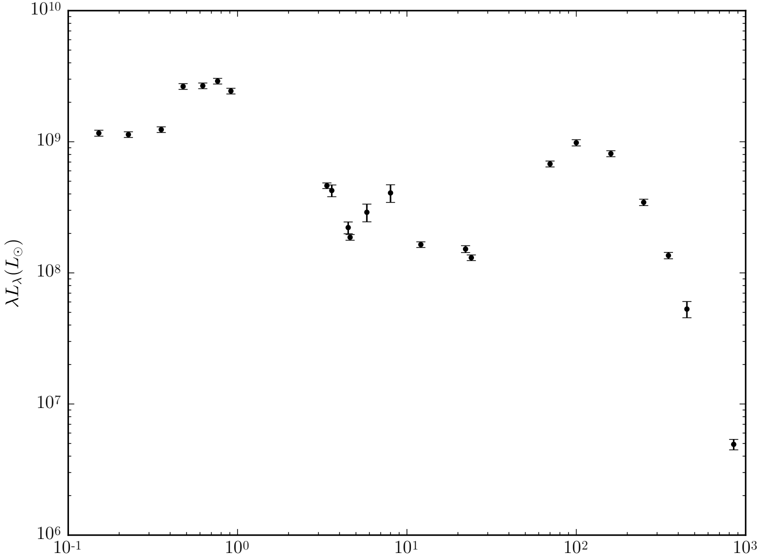
Submillimetre/IR data

- WISE: 3.4, 4.6, 12, 22μm
- IRAC: 3.6, 4.5, 5.8, 8μm
- MIPS: 24, 70μm
- PACS: 100, 160μm
- SPIRE: 250, 350μm
- SCUBA-2: 450, 850μm

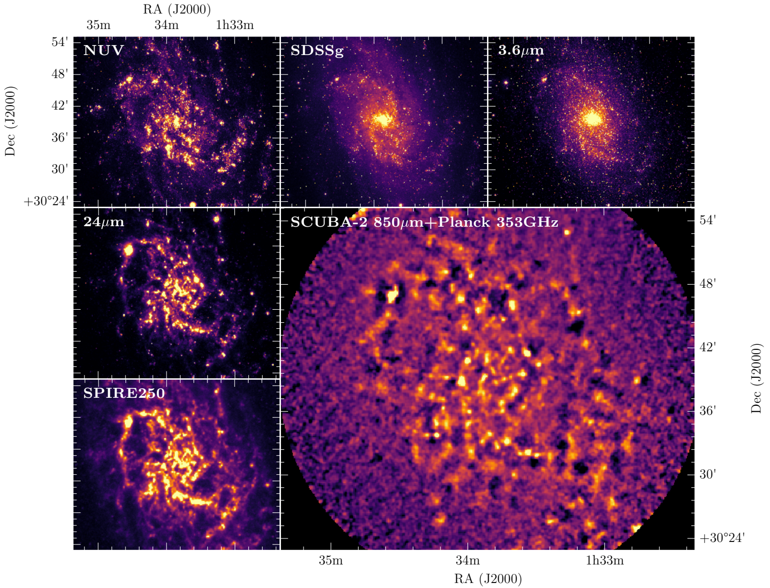
UV/Optical data

- GALEX: FUV/NUV
- SDSS: u, g, r, i, z

A Panchromatic Data Set

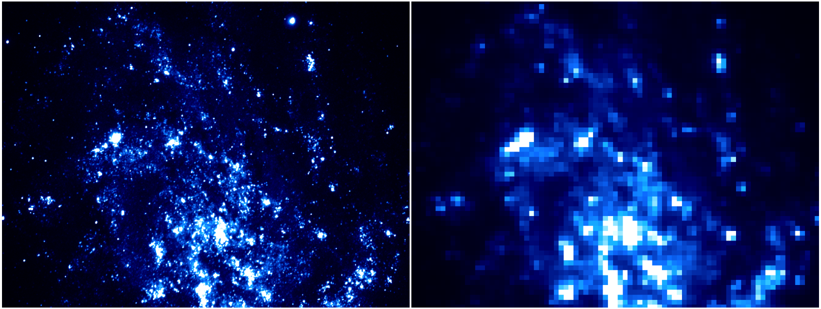


A Panchromatic Data Set



Preparing Data

- Need all data at common pixel scale and resolution
- Convolve to SPIRE 350 beam – FWHM = 25"
- Regrid to pixels of 25" so statistically independent
- This is $\sim$ 100pc at the distance of M33, roughly the size of a GMC



TIR Luminosity

Firstly, calculate SFR from total infrared (TIR) luminosity

- Traces obscured star-formation, assumes dust heated entirely by young stars, and all light absorbed by dust
- Use Kennicutt & Evans (2012) prescription, integrating from 3-1100μm:

$$\log_{10}(\mathrm{SFR_{TIR}}) = \log_{10}(L_{\mathrm{TIR}}) - 43.41 \qquad (2)$$

TIR luminosity gives a total SFR of $0.17 \pm 0.06\ M_{\odot}/\mathrm{yr}$

FUV+24μm

Also trace SFR using combination of FUV+24μm:

- FUV traces unobscured star-formation over a timescale of ~10-100Myr (e.g. Kennicutt, 1998)
- This should correct for the starlight we're not seeing re-emitted from the dust
- Use Leroy+ (2008) prescription to get SFR density:

$$\Sigma_{\mathrm{SFR}} = 8.1 \times 10^{-2} I_{\mathrm{FUV}} + 3.2^{+1.2}_{-0.7} \times 10^{-3} I_{24} \quad (3)$$

FUV+24μm gives a total SFR of $0.26^{+0.11}_{-0.07}\ M_{\odot}/\mathrm{yr}$

MAGPHYS

Finally, calculate SFR using MAGPHYS. Briefly, MAGPHYS:

- Uses a library of optical and IR models
- Allows for bursty star-formation history, and variations in SFR down to 1Myr
- Finds the best fit to the data from these models
- Gives a bunch of properties of the galaxy
- Also gives an error on the modelling for each of these quantities

MAGPHYS gives a total SFR of $0.33^{+0.05}_{-0.06}\ M_{\odot}/\mathrm{yr}$

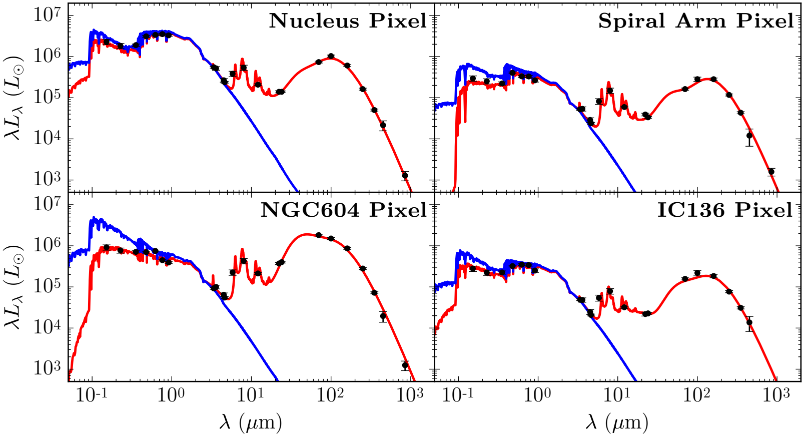
Pixel-by-pixel fits

Calculate for all pixels within an ellipse of $60' \times 70'$ (19000 pixels!)...need some way to filter out pixels we don't trust

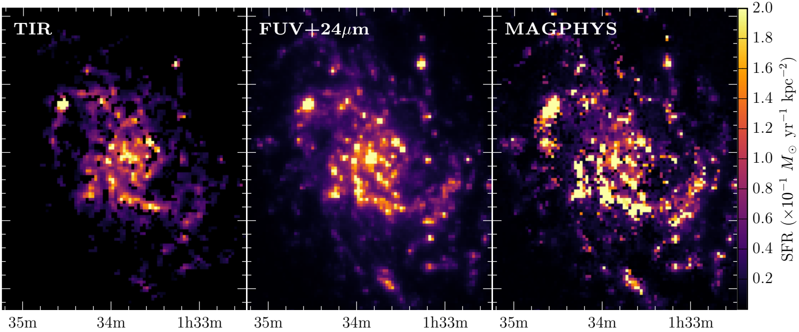
- TIR: Only fit pixels with S/N>2.5 in at least 4 *Herschel*/SCUBA-2 bands
- FUV+24μm: Filter using a S/N cutoff on the SFR map
- MAGPHYS: Filter based on percentiles – remove any pixels that do not satisfy

$$0.5 \times \frac{p_{86} - p_{16}}{p_{50}} < 0.32 \qquad (4)$$

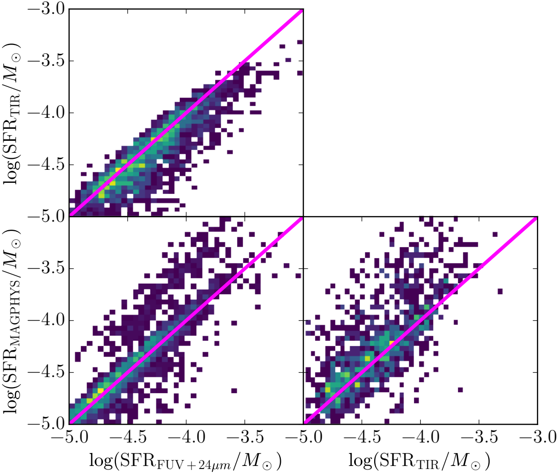
Example SEDs



SFR Maps


TIR
FUV+24μm
MAGPHYS
35m
34m
1h33m
35m
34m
1h33m
35m
34m
1h33m
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
SFR (×10⁻¹ M☉ yr⁻¹ kpc⁻²)

SFR Comparisons

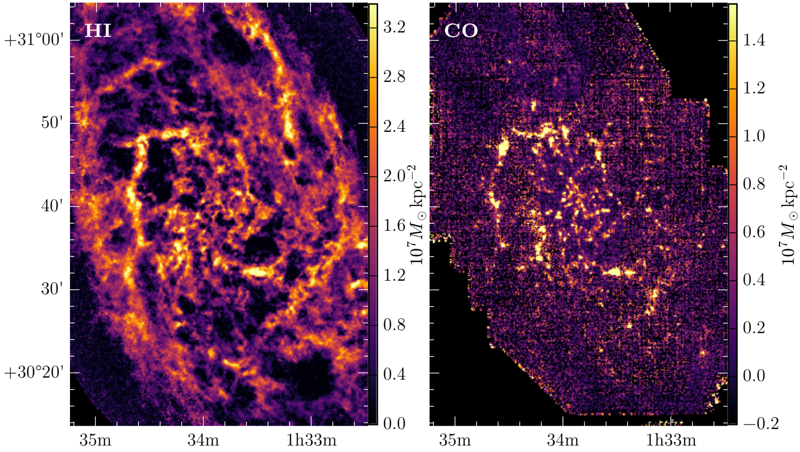


Use MAGPHYS going forwards

Gas

- Trace atomic hydrogen with H I 21cm (VLA; Thilker+, 2005)
- Trace molecular hydrogen with CO(J=2-1) from IRAM (Druard+, 2014)
- Theoretically, we can also trace total gas using the dust continuum (Eales+, 2012; Madgis+, 2012)

Gas


HI
CO
+31°00'
50'
40'
30'
+30°20'
35m
34m
1h33m
3.2
2.8
2.4
2.0
1.6
1.2
0.8
0.4
0.0
$10^7 M_\odot\,\mathrm{kpc}^{-2}$
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
−0.2

Calculating Gas Masses

- Convert the 21cm line directly - from Rohlfs & Wilson (1996):

$$\Sigma_{\text{HI}} = 1.8 \times 10^{18}\text{cm}^{-2}/(\text{K km/s}) \tag{5}$$

Gives a total HI mass of $5 \times 10^8 M_\odot$

- For CO, use Braine+ (2010) values:

$$X_{\text{CO}} = \begin{cases} 1.54 \times 10^{20}\text{cm}^{-2} & \text{if } R < 2\text{kpc} \\ 2.87 \times 10^{20}\text{cm}^{-2} & \text{if } R \geq 2\text{kpc} \end{cases} \tag{6}$$

- Convert from J=1-0 to J=2-1 with fixed ratio

$$\text{CO}\left(\frac{2-1}{1-0}\right) = 0.7 \tag{7}$$

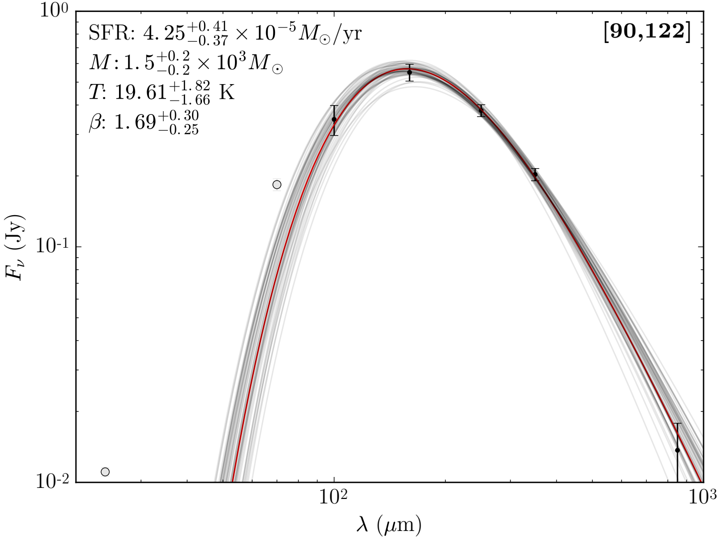
Gives a total H_2 mass of $4.5 \times 10^7 M_\odot$

Dust: MBB Fitting

First, create dust map with one-temperature modified blackbody (MBB) fitting:

- Use variable dust emissivity, β
- Assume dust absorption coefficient, $\kappa_{850} = 0.77 \mathrm{cm}^2 \mathrm{g}^{-1}$ (Dunne+, 2000)
- Fit for all pixels with S/N$>$ 2.5 in at least 4 bands, for at least one degree of freedom
- Errors provided by MCMC analysis

Dust: MBB Fitting



Dust: MAGPHYS

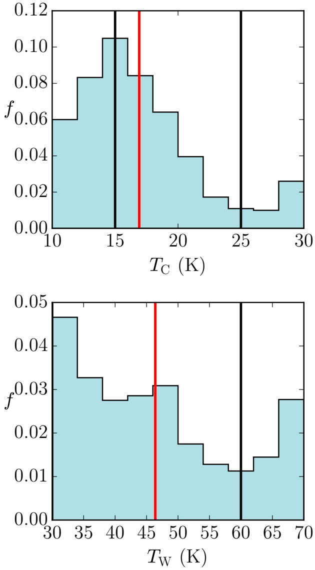
Also use MAGPHYS to model dust continuum:

- Incorporates polycyclic aromatic hydrocarbons (PAHs)
- Models dust as a series of greybodies with temperatures of 850, 250 and 130K
- Models warm dust as MBB with $\beta = 1.5$, between 30-60K
- Models cold dust as MBB with $\beta = 2$, between 15-25K

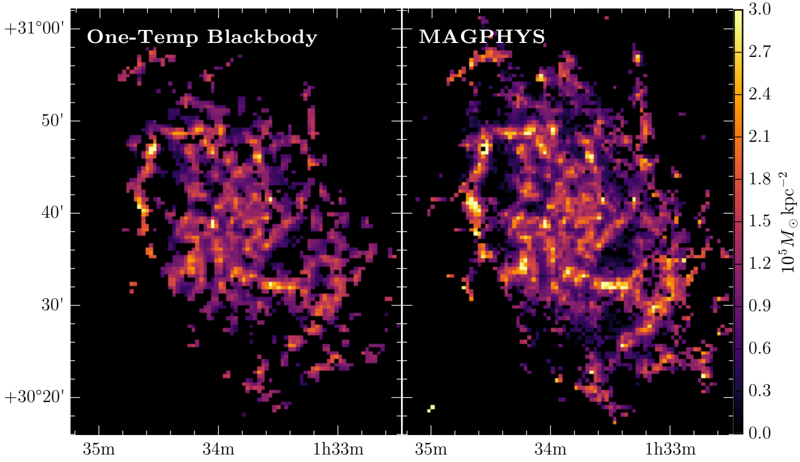
Dust: MAGPHYS

However...

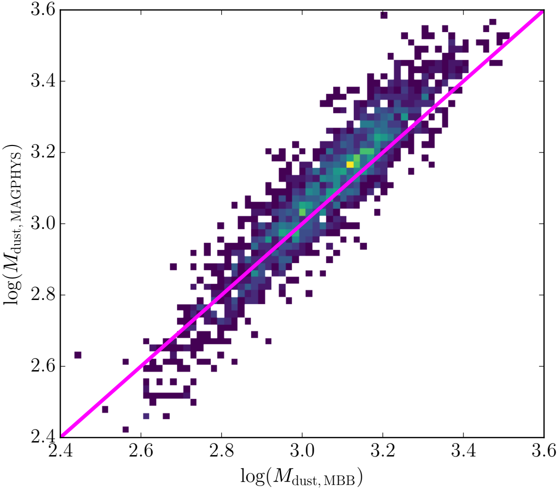
- $\sim$40% of pixels lie outside this range
- Use extended IR library (courtesy of Sébastien Viaene)
- Increases parameter space of the cold dust temperature from 10K $< T_C <$ 30K and warm dust temperature to 30K $< T_W <$ 70K



Dust


One-Temp Blackbody
MAGPHYS
+31°00'
50'
40'
30'
+30°20'
35m
34m
1h33m
35m
34m
1h33m
3.0
2.7
2.4
2.1
1.8
1.5
1.2
0.9
0.6
0.3
0.0
$10^5 M_\odot \, \mathrm{kpc}^{-2}$

Dust Model Comparison



Converting dust to gas mass

- Use gas-to-dust ratio (GDR)
- For M33, this rises from $\sim$200 in the centre of the galaxy to $\sim$400 in the outer disk (Gratier+, 2017)
- This variation is logarithmic with radius:

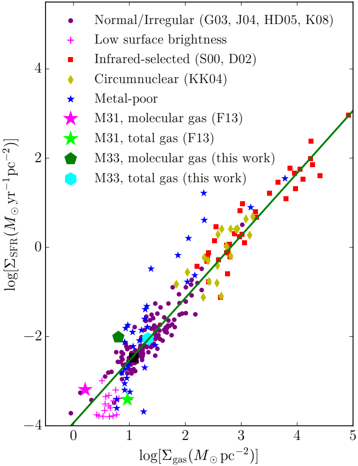
$$\log(\mathrm{GDR}) = 0.07R + 2.26 \tag{8}$$

Gas Comparisons

	H I	H_2	Total gas	MBB	MAGPHYS
ρ_{sp}	0.22*	0.38*	0.36*	0.18*	0.23*
ρ_{pears}	0.23*	0.40*	0.41*	0.17*	0.24*

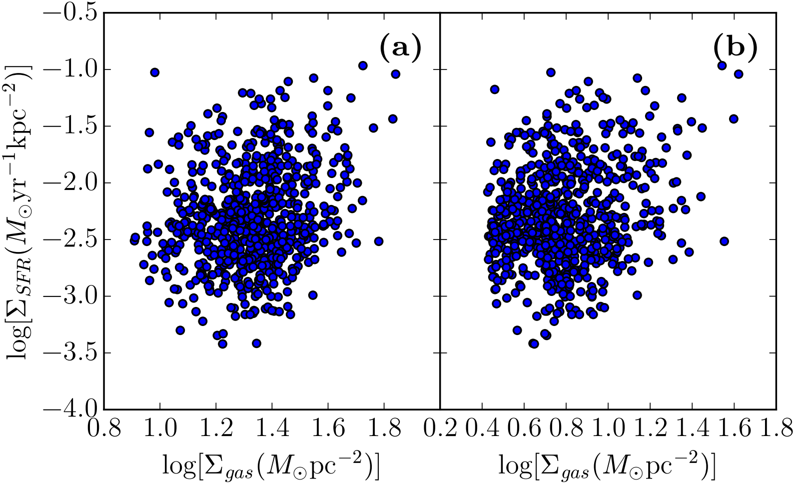
Use H_2 and total gas going forwards

Global fits



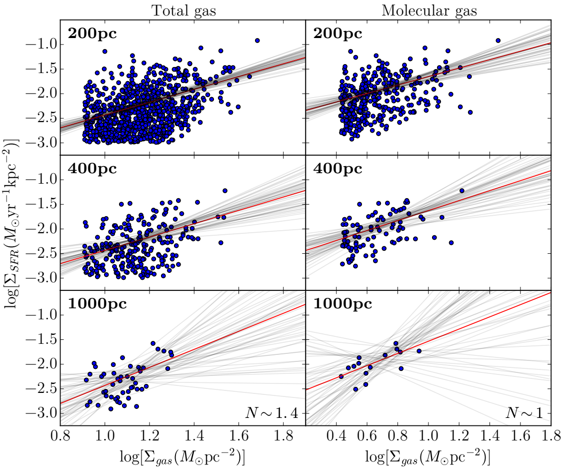
Consistent with previous studies

Pixel-by-pixel fitting



SF law has broken down at ∼100pc

Variation with pixel scale

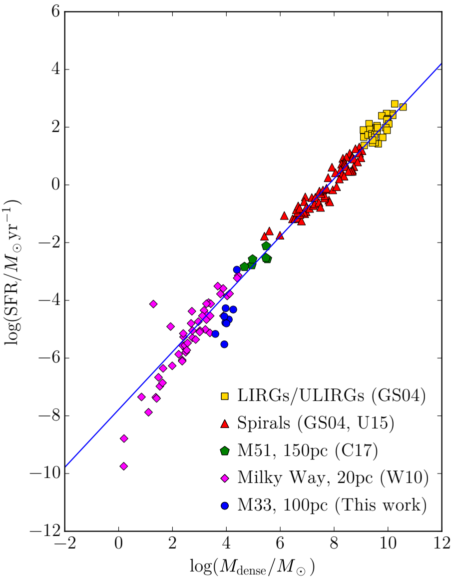


Stronger correlation at larger pixel scales; superlinear with total gas and linear with molecular?

Dense Gas

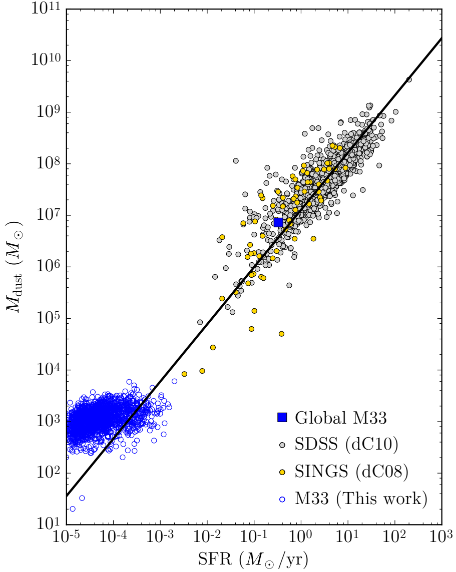
- Use HCN(J=1-0) to trace dense molecular gas
- Pointings from IRAM 30m telescope, FWHM ~100pc at distance of M33
- Various pointings – most from Buchbender+ (2013), but complementary measurements from Rosolowsky+ (2011) and Braine+ (2017)
- Match up to SFR map

Dense Gas



6
4
2
0
−2
−4
−6
−8
−10
−12
log(SFR/$M_\odot$ yr^{-1})
−2
0
2
4
6
8
10
12
log($M_{\rm dense}/M_\odot$)
LIRGs/ULIRGs (GS04)
Spirals (GS04, U15)
M51, 150pc (C17)
Milky Way, 20pc (W10)
M33, 100pc (This work)

SFR/$M_{\rm dust}$



$M_{\rm dust}$ $(M_\odot)$
SFR $(M_\odot/{\rm yr})$
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
Global M33
SDSS (dC10)
SINGS (dC08)
M33 (This work)

Conclusions

- MAGPHYS is useful for tracing sub-kpc star-formation since it traces down to ~1Myr
- Molecular gas and total gas from CO+HI best trace star-formation in M33
- At 100pc, correlations are very weak – the star-formation law has broken down
- At larger spatial scales, a linear *N* is appropriate for molecular gas, superlinear for total gas
- Much stronger correlations between SFR and dense gas
- SFR also correlates better with dust mass, but metallicity-dependent slope

Further work

- Higher S/N SCUBA-2 maps – 64 $\rightarrow$ 12mJy/beam at 450μm
- Use this 450μm map to create a GMC catalogue at $\sim$30pc resolution
- Use these M33 maps to refine combining SCUBA-2 data with *Herschel* 500μm and Planck 353GHz data
- Detailed SED fitting – try to break the T/β anti-correlation
- Dark gas
- Very cold ($T < 10$K) dust?

Thanks for Listening

Any questions?