The star formation law in Tidal Dwarf Galaxies

Ute Lisenfeld
Universidad de Granada (Spain)

In collaboration with:
Jonathan Braine
Pierre-Alain Duc
Mederic Boquien
Elias Brinks
Frederic Bournaud
Federico Lelli
Vassilis Charmandaris
The star formation law

- How do stars form from gas?
  ➔ Compare (molecular) gas mass and star formation rate.
- For spirals, the molecular gas depletion time (\(=M_{\text{H}_2}/\text{SFR} = \text{SFE}^{-1}\)) is \(\approx 2\) Gyr (Leroy+08, Bigiel +08,11), shorter for starbursts (e.g. Genzel+10,Daddi10).

- **What is the physical cause of this relation?**
  ➔ Study diverse objects/environments
  ➔ Search for deviations from “normal” KS-law

Kennicutt-Schmidt law (Kennicutt & Evans 2012)
The SF law on the faint end

- **Low surface brightness galaxies** *(Wyder+09)*: Low SFR/MHI (but no CO detected) – most likely due to a low molecular gas fraction.

- **Outer spirals disks** *(Schruba+11)*: SFR/M$_{\text{HI}}$ is low
  - Stacking CO $\Rightarrow$ M$_{\text{H}_2}$/M$_{\text{HI}}$ is low
  - SFR/M$_{\text{H}_2}$ is the same as in the inner disk
  - $\Rightarrow$Molecular gas formation is low at outer radii, but SF from molecular gas is normal

- **Dwarf galaxies**: Problem: M$_{\text{H}_2}$ hard to measure because X-factor is not well known for low metallicty.

- Here we study **Tidal Dwarf Galaxies (TDGs)** for the following reasons.....
Tidal Dwarf Galaxies

- Form out of gas and stellar debris at the end of tidal tails.
- Gaseous and stellar properties: similar to classical dwarf irregular and blue compact dwarfs, except ….

… their high metallicity

- typical of outer regions of spiral galaxies: $12 + \log(O/H) \approx 8.4-8.6$
- do not follow luminosity-metallicity relation

… and their low dark matter content:

- Predicted from simulations (e.g. Barnes & Hernquist 1992)
- $M_{\text{dyn}}/M_{\text{vis}} \approx 1$ (Bournaud et al. 2003, Lelli et al. 2015, in 6 TDGs in 3 systems)
NGC 4694 and VCC 2062

- Situated at the outskirts of the Virgo Cluster close-by (D = 17 Mpc)
- NGC 4694 and VCC 2062 have same recession velocity.
- NGC 4694: SB0 peculiar
- VCC 2062: very low surface brightness dwarf galaxy ($\mu_v = 25.5$ mag/"")

Combined u,g,i image from the NGVS (Next Generation Virgo cluster Survey, Ferrarese et al. 2012)
NGC 4694 and VCC 2062

- Stellar bridge between both galaxies -> evidence that VCC 2062 is physically related to NGC 4694
- NGC 4694 is distorted and assymetric -> old merger

Deep g-band image from the NGVS (New Generation Virgo Survey, Ferrarese et al. 2012)
Optical and HI (blue)
SF regions in the tail

NGC 4694

VCC 2062

HII-a

HII-b
Dynamical mass from HI kinematics

Analysis of the HI kinematics (Lelli et al. 2015)

VLA HI data (resolution 14.7”x14.3”)

Model HI disk adopting PA, i, \( v_{\text{sys}} \), flat rotation curve (\( V_{\text{rot}}, R_{\text{out}} \)) and fit to the HI data

Good fit, with residual HI (most likely tail material).

Derive dynamical mass, and compare to baryonic mass

\[ M_{\text{bar}} = M_{\text{gas}} + M_{\text{star}} \]

\[ \rightarrow \frac{M_{\text{dyn}}}{M_{\text{bar}}} = 1.0 \pm 0.9 \]

\[ \rightarrow \text{Consistent with no dark matter} !! \]

\[ \rightarrow \text{Strong evidence that VCC 2062 is a TDG} \]
CO(1-0) observations with PdBI

Field of View covered by PdBI

- Observations done in C and B conf.
- Original resolution 3.22''x 2.37'' ($\approx$300pc)

Velocity integrated CO(1-0) emission
CO(1-0) spectra

Line width in each region about 20 km/s

NE: $M_{\text{H}_2} = 1.1 \times 10^7$ Msun

SW: $M_{\text{H}_2} = 6.5 \times 10^6$ Msun
Comparison to HI

- NE clouds coincides with peak of HI
- SW cloud is between the two HI peaks
- CO is less extended than HI
- Kinematics of CO and HI agree where they overlay.
Comparison to star formation

- Good coincidence between CO and SF tracers in NE region
- Weaker SF in SW region (but present, see 8µm)
Measure SFR

- Integrate SF tracers in the same apertures as CO
- Use different tracers (Hα, UV, 8/24µm, 8/24µm+ Hα/UV)
- Apply standard conversion from luminosities to SFR (Kennicut & Evans 2012)

- Modelling of UV-optical-IR SED with CIGALE for the entire galaxy.
  - Present SFR = \( 3 \times 10^{-3} \, \text{Msun yr}^{-1} \)
  - Averaged SFR (past \( 10^8 \) yr) = \( 4.5 \times 10^{-3} \, \text{Msun yr}^{-1} \)
  - Total stellar mass = \( 7 \times 10^6 \) Msun
Molecular gas and SF

- Recent SF tracers (Hα, 8/24µm) give low $\Sigma_{SFR}$ compared to $\Sigma_{H2}$.
- Especially low in region SW.
- Long term SF tracer are more in agreement with SFE of spiral galaxies.

Bigiel et al. (2011) (Herakles)
Why is SFE so low?

Low gas surface density?

• VCC 2062 has:
  – low surface brightness: $\mu_v = 25.5$ mag/"$^2$
  – low stellar mass surface density: 1 Msun pc$^{-2}$
  – low gas surface density: $\Sigma_{\text{gas}} \approx 6$ Msun pc$^{-2}$
  – At these low surface densities, $\Sigma_{\text{SFR}}/\Sigma_{\text{gas}}$ decreases usually – but also $M_{H_2}/M_{\text{HI}}$

• VCC 2062 does have considerable molecular gas, with $M_{H_2}/M_{\text{gas}} \approx 50%$
  $\Rightarrow$ molecular gas to form stars is present.
Why is SFE so low?

**Decreasing SFR:**

- CIGALE fitting: SFR(average $10^8$ yr) ≈ 1.5 x present SFR
- Consistent with low SFR(Hα)/SFR(UV)
  ➔ Non equilibrium situation; few massive stars compared to continuous SFR for which indicators are calibrated.

**Low SFR (∼10^{-3} Msun yr^{-1})**

- Stochastic sampling of IMF ➔ few O stars are being formed
- Difference in expected L(Hα) can be factor of 2 for SFR < 10^{-3} Msun yr^{-1} (Cerviño 2003, Cerviño & Luridiana 2004)
Does orbital time play a role?

Gas consumption for star formation is about 10% per orbital time.
Does orbital time play a role?

- VCC 2062 has a long $\tau_{\text{orb}}$ (1.2x$10^9$ yr) due to lack of dark matter.
- Gas consumption per orbit is $\approx$ 10%, as in spiral galaxies.

BUT: - What could be physical cause?
- VCC 2062 is different from other TDGs.
How is the SF law in TDGs?

For most objects there is only single-dish data.

- **Blue:** single dish CO data.
- **Red:** Interferometric CO data

- **Lines:** Relation found by Bigiel (2008), and 0.2 dex scatter range (no helium fraction)

- **SFR** \( (M_\odot \, yr^{-1}) = 5.3 \times 10^{-39} \, L(H\alpha) \) (erg s\(^{-1}\)) (Kennicutt 1998, adapted for Kroupa IMF)

- **SFR for Arp 158** from FUV and 24 \( \mu m \) (Boquien et al. 2011)

- **SFR for Arp 245** from 24 \( \mu m \) and H\(\alpha\)

→ In general (except of VCC 2062) reasonable agreement with relation found by Bigiel et al. (2008).
Summary

• TDGs are interesting objects to study the SF law, because of:
  – High metallicity -> CO is a good tracer of the molecular gas
  – Low dark matter content -> different conditions
• VCC 2062 is an old, nearby TDG with a large data set
• Interferometric observations of the molecular gas together with the measurement of the SFR from different tracers a low SFE for VCC 2062. Possible reasons are:
  – Declining SFR in the past
  – Short orbital time
• For other TDGs with CO the SFE is similar to that in spiral galaxies.