Green Peas
– the X-ray brightest star forming galaxies?

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X-ray Astronomy 2019, Bologna, 10th Sep 2019
Green Peas (GPs)

- compact, low-mass ($\approx 10^9 M_\odot$), highly star-forming ($\approx 10 M_\odot$/yr) galaxies at redshift $z \approx 0.2-0.3$ (Cardamone et al., 2009)
- strong UV Ly$\alpha$ lines, comparable to high-z starburst galaxies known as Lyman-Alpha Emitters (Henry et al. 2015, Verhamme et al. 2017, Orlitová et al. 2018)
- some were found to be leaking Lyman continuum (Verhamme et al. 2017, Izotov et al. 2018)
Lyman Continuum (LyC) escape

- LyC efficiently ionizes hydrogen atoms
- LyC leakage from star-forming galaxies could play an important role in Re-ionisation of the Universe
  - quasars represent a competitive scenario
- LyC escape reported in several GPs
  - the fraction of LyC escape varies from 5 to 70% (Izotov+18)
  - star forming galaxies numerous in early Universe, 20% of leakage should be sufficient (Yajima+09, Paardekooper+15)
  - GPs share the same properties with high-z star-forming galaxies and thus can be considered as their low-redshift analogs
Optical characteristics of Green Peas

- optical sky survey with SDSS
- GPs discovered by citizen project on galaxy classification
- most GPs are purely star-forming galaxies according to the optical lines
- what are their X-ray properties?
Our project with XMM-Newton

• XMM-Newton observed three GPs (PI M. Ehle)
  • sources selected as purely star-forming according to the BPT classification
  • highest SFR (SFR ≈ 20-60 M$_\odot$/yr) – to maximize chance of X-ray detection

<table>
<thead>
<tr>
<th>source</th>
<th>redshift</th>
<th>SFR$^a$ [M$_\odot$/yr]</th>
<th>Metallicity$^b$ Log[O/H] + 12</th>
<th>Net count rate [10$^{-3}$ cts/s]</th>
<th>L$_x$ (0.5-8 keV, rest frame) [10$^{42}$ erg s$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDSSJ074936.7+333716 (GP 1)</td>
<td>0.2733</td>
<td>58.8</td>
<td>8.3</td>
<td>3.1 ± 0.7</td>
<td>1.2 ± 0.4</td>
</tr>
<tr>
<td>SDSSJ082247.6+224144 (GP 2)</td>
<td>0.2162</td>
<td>37.4</td>
<td>8.1</td>
<td>6.4 ± 0.7</td>
<td>1.2 ± 0.3</td>
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<tr>
<td>SDSSJ133928.3+151642 (GP 3)</td>
<td>0.1920</td>
<td>18.8</td>
<td>8.1</td>
<td>-</td>
<td>&lt; 0.13</td>
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$^a$ SFR determined from H$_\alpha$ (Cardamone+09)

$^b$ we measured metallicity based on O3N2 method (Pettini&Pagel, 04)

03N2 method employs [O III]λ5007/H$\beta$ and [N II]λ6583/H$\alpha$ emission line ratios
X-ray images

**GP 1:**
clear detection in soft X-rays (<2 keV)

**GP 2:**
detection in full X-ray band (0.5-10 keV)

**GP 3:**
no clear detection
X-ray spectra

- different spectral slope:
  - $\Gamma \approx 3$ for GP1
  - $\Gamma \approx 2$ for GP2
Measured X-ray luminosity

- GP 1 and GP 2 are largely above different L_x-SFR- (metallicity) empirical relations
- their X-ray excess is of order of $10^{42}$ erg/s
- GP 3 only upper limit consistent with predictions
Comparison with other star-forming galaxies

- \( L_X \)-SFR-metallicity relation based on *Brorby et al. 2016*
- GP 1 and GP 2 are significantly above the correlation
- are X-ray brighter than Lyman-Break Analogs, Lyman-Break Galaxies, Green Pea Analogs, or other nearby star forming galaxies
Explanation of the X-ray excess

• stochasticity?
  • cannot explain dispersion at high SFR
  • Gilfanov+04 showed that the probability of detecting $L_x = 2 \langle L_x \rangle$ is $p < 0.001$
    for $SFR \approx 40 \, M_\odot/yr$ (see also, Justham & Schawinski 12), our GPs have $SFR \approx 20-60 \, M_\odot/yr$
Explanation of the X-ray excess

• stochasticity?  X

• larger number of HMXBs? (due to different IMF?)
  • number of HMXBs: \( N \approx 13 \) SFR (Gilfanov & Merloni, 2014)
  • measured \( L_x \) is at least 4-6x larger than predicted
    \[ \rightarrow \text{SFR from } L_x \text{ excess is } \text{SFR} \approx 300 \text{ M}_\odot/\text{yr} \]

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<th>SFR (from ( H\alpha ))</th>
<th>( N ) (HMXB) expected</th>
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<td>GP 1</td>
<td>58.8</td>
<td>764</td>
<td>3000</td>
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<td>37.4</td>
<td>486</td>
<td>3400</td>
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Explanation of the X-ray excess

• stochasticity?  X
• larger number of HMXBs?  ?
• ULXs?  SNe?
  • observed in star forming galaxies (Basu-Zych+13, Kaaret+17)
  • X-ray luminosity of ULXs is $10^{39}-10^{41}$ erg/s, at least 10-1000 ULXs needed to explain the observed X-ray excess
  • luminous SNe?  (see talk by Dwarkadas)
    • for SFR $\approx 50$ $M_\odot$/yr star with $M > 8M_\odot$ every 2-3 years
Explanation of the X-ray excess

• stochasticity?  X
• larger number of HMXBs?  ?
• ULXs? SNe?  ?
• hot gas?
Explanation of the X-ray excess – hot gas?

- simulations of hot gas X-ray luminosity from star clusters do not reach the observed luminosity of GPs

Franeck et al., in prep.
Explanation of the X-ray excess

• stochasticity? X
• larger number of HMXBs? ?
• ULXs? Sne? ?
• hot gas? X
• AGN?
Explanation of the X-ray excess – AGN?

- comparison of GPs with LBAs with the composite spectrum (Jia+11)
Explanation of the X-ray excess

- stochasticity?  X
- larger number of HMXBs?  ?
- ULXs? SNe?  ?
- hot gas?  X
- AGN?  ?

- the excess is present in two out of three GPs
  - GP2 and GP3 very similar in optical light, but largely different in X-rays
  - easiest to be explained by an AGN (on/off), probably with $M_{\text{BH}} < 10^5 M_\odot$
Conclusions

• XMM-Newton observations of three Green Pea galaxies showed a significant X-ray excess of $L_x \approx 10^{42}$ erg/s in GP 1 and GP 2

• the X-ray excess needs to be of the physical origin
  • possible explanations include AGN (IMBH), ULXs, IMF?
  • is not present in all GPs, not simply related to SFR or metallicity

• more deep X-ray observations of similar sources desired

• more details in our recent paper:

Thank you very much for your attention!!!
Measured X-ray luminosity

\[ \log_{10}(L_x [\text{2-10 keV}]/\text{SFR}) \]

- LSFGs - Colbert et al. (2004)
- LSFGs - Mineo et al. (2011)
- LIRGs/ULIRGs - L10, hw11
- LBAs - Brorby et al. (2016)
- GPs - Brorby et al. (2017)
- Stacked LBGs - Basu-Zych et al. (2013)
- GPs - This work

- LMXB dominated
- HMXB dominated

- GP1
- GP2
- GP3

- Mineo et al. (2012)

\[ \log_{10}(L_x [\text{2-10 keV}]/\text{SFR}) \]
Comparison of different SFR methods
XMM-Newton look at Green Peas

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Measured X-ray luminosity

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