The Local Group as a Time Machine

Dan Weisz
Hubble Fellow
University of Washington

Collaborators:
Mike Boylan-Kolchin (MBK)
James Bullock
Charlie Conroy
Ben Johnson

#LGAsstat
Michigan
6.4.2015
A Primary Goal of high-z galaxy studies (HUDF, JWST, FF): Find, count, & characterize galaxies during reionization.
Galaxy Ultra-Violet Luminosity Function at z~7

More

Number Density

Less

Brighter

M_{UV}

Fainter

Finkelstein+ 2014

M^* = -21.03^{+0.37}_{-0.50}

\alpha = -2.03^{+0.21}_{-0.20}

\varphi^* = 1.57^{+1.49}_{-0.95} \times 10^{-4}
Galaxy Ultra-Violet Luminosity Function at z~7

![Graph showing the luminosity function with data points from various studies, including This Study, Tilvi+13, Bouwens+14, Castellano+10, McLure+13, Ouchi+09, Schenker+13, Bowler+14, and Bouwens+11. The graph includes points for the number density on a logarithmic scale, with M^* = -21.03^{+0.37}_{-0.50}, \alpha = -2.03^{+0.21}_{-0.20}, and \varphi^* = 1.57^{+1.49}_{-0.95} \times 10^{-4}.](image)
Galaxy Ultra-Violet Luminosity Function at $z \sim 7$

This Study

Tilvi+13

Bouwens+14

Castellano+10

McLure+13

Ouchi+09

Schenker+13

Bowler+14

Bouwens+11

$M' = -21.03^{+0.37}_{-0.50}$

$\alpha = -2.03^{+0.21}_{-0.20}$

$\varphi' = 1.57^{+1.49}_{-0.95} \times 10^{-4}$
Galaxy Ultra-Violet Luminosity Function at z~7

More

Number Density

Less

Brighter

M_{UV}

Fainter

Needed to maintain reionization

(e.g., Kuhlen+ 2012, Robertson+ 2013, 2015)

\[ M^* = -21.03^{+0.37}_{-0.50} \]

\[ \alpha = -2.03^{+0.21}_{-0.20} \]

\[ \psi = 1.57^{+1.49}_{-0.96} \times 10^{-4} \]
Galaxy Ultra-Violet Luminosity Function at z~7

More

Number Density

Less

Brighter

M_{UV}

Fainter

$M^* = -21.03^{+0.37}_{-0.50}$

$\alpha = -2.03^{+0.21}_{-0.20}$

$\varphi^* = 1.57^{+1.49}_{-0.05} \times 10^{-4}$

HUDF

Needed to maintain reionization

(e.g., Kuhlen+ 2012, Robertson+ 2013, 2015)
Galaxy Ultra-Violet Luminosity Function at $z \sim 7$

**More**

- $10^3$
- $10^2$
- $10^1$
- $10^0$
- $10^{-1}$
- $10^{-2}$
- $10^{-3}$
- $10^{-4}$
- $10^{-5}$
- $10^{-6}$
- $10^{-7}$

**Less**

- $10^{-13}$
- $10^{-14}$
- $10^{-15}$
- $10^{-16}$
- $10^{-17}$
- $10^{-18}$
- $10^{-19}$
- $10^{-20}$
- $10^{-21}$
- $10^{-22}$
- $10^{-23}$

**Number Density**

$M' = -21.03^{+0.37}_{-0.50}$

$\alpha = -2.03^{+0.21}_{-0.20}$

$\phi^* = 1.57^{+1.49}_{-0.95} \times 10^{-4}$

**HUDF**

**HST FF (5x, 10x)**

**Needed to maintain reionization**

(e.g., Kuhlen+ 2012, Robertson+ 2013, 2015)
Galaxy Ultra-Violet Luminosity Function at $z \sim 7$

**Figure:** Galaxy Ultra-Violet Luminosity Function at $z \sim 7$

- More
- Less

**Axes:**
- Number Density
- $M_{UV}$

**Legend:**
- This Study
- Tilvi+13
- Bouwens+14
- Castellano+10
- McLure+13
- Ouchi+09
- Schenker+13
- Bowler+14
- Bouwens+11

**Equations:**
- $M^* = -21.03^{+0.37}_{-0.50}$
- $\alpha = -2.03^{+0.21}_{-0.20}$
- $\varphi^* = 1.57^{+1.49}_{-0.95} \times 10^{-4}$

**Notes:**
- The figure shows the luminosity function for galaxies at $z \sim 7$ with higher number density at brighter magnitudes.
- The fit parameters are given as $M^*$, $\alpha$, and $\varphi^*$.
- The figure includes data points from various studies and shows the trend as more data becomes available with JWST.

**Reionization:**
- Needed to maintain reionization
  (e.g., Kuhlen+ 2012, Robertson+ 2013, 2015)
Reionization and Small Scale Structure in $\Lambda$CDM

**Clever idea:** Look for faint galaxies at epoch of reionization

**Problem:** Faint galaxies are hard to observe!

**Another clever idea:** Use the stellar fossil record of nearby dwarfs galaxies to study faint galaxies at epoch of reionization

or

where on the high-z UVLF do LG dwarf galaxies live?
The Stellar Fossil Record

Study Galaxy Evolution by Resolving Individual Stars

Outside MW Common Distance, Foreground extinction + Stellar Evolution

Bright

Young

Old

~Log Luminosity

HOT

Color

COOL

Faint
Color-Magnitude Diagrams (CMDs)
CMDs are Information Rich

**CMD Fitting Ingredients**

- Stellar evolution model
- IMF
- Stellar multiplicity
- Age basis functions (~100)
- Metallicity basis function (~20)
- Distance
- Reddening (~1-10 components)
- Noise model
- Star-by-star fitting vs. binned CMD
- Grid Search
- MCMC
- Simulated Annealing
- …

Computing and reporting uncertainties
CMDs are Information Rich

**CMD Fitting Ingredients**

**Stellar Evolution Model**
- IMF
- Stellar Multiplicity

Noise model
- age basis functions (~100)
- metallicity basis function (~20)
- distance
- reddening (~1-10 components)

**Star-by-star fitting vs. binned CMD**

**Grid Search**
- MCMC
- Simulated Annealing

...
Example Star Formation History

Fornax LG dSph

SFH from Fossil Record $\rightarrow M_\star(z)$

Weisz+ 2014a
Example Star Formation History

SFH from Fossil Record $\rightarrow M_\star(z)$

Fornax
LG dSph

Ancient
Constant
Young
Stellar Fossil record cannot resolve sub-Gyr SF events at epoch of reionization
Onorbe+ 2015; MBK+ 2015

Use Simulations of Dwarfs as Guide for ‘Burstiness’ of SFHs at high-z

On 200 Myr Timescales: Smoothly varying SFR, modest bin-to-bin contrast
On 20 Myr Timescales: Rapidly varying SFR, high (5-20) bin-to-bin contrast
**M_{UV}** distributions at z~7 for Fornax for select burst models

200 Myr bursts

20 Myr bursts

SFH from Fossil Record → M_*(z)

M_*(z) + Bursts + population synthesis → M_{UV}(z)

Weisz+ 2012, 2014; MBK+2015
Repeat exercise to get $M_{UV}$ at $z \sim 7$ for many LG Dwarf Galaxies

$M_V = -4.9 \sim 10^4 M_\odot$

dSph dIrr dTrans dE

Plus newer data
Cole+ 2007, 2014
Hidalgo+ 2011
Monelli+ 2010
Brown+ 2014
…

$M_V = -16.5 \sim 10^9 M_\odot$
The Local Group in high-z context

What did the progenitors of Local Group dwarfs look like at high redshift?

How will galaxies that are observable with current and future observatories evolve to the present day?

Local Group Dwarf Galaxies at z~7

\[ \log_{10}(M_{\text{vir}}/M_\odot) \text{ at } z\sim7 \]

Number Density

\[ M_{\text{UV}} \]

Less

Brighter

Atef; \langle z \rangle = 6.26

Finkelstein; \langle z \rangle = 6.96

MBK+ 2015
The Local Group in high-z context

What did the progenitors of Local Group dwarfs look like at high redshift?

How will galaxies that are observable with current and future observatories evolve to the present day?

MBK, Weisz, et al. 2015

Local Group Dwarf Galaxies at z~7

\[ \log_{10}(M_{\text{Vir}}/M_\odot) \text{ at } z\sim7 \]

MBK+ 2015
The Local Group in high-z context

What did the progenitors of Local Group dwarfs look like at high redshift?

How will galaxies that are observable with current and future observatories evolve to the present day?

MBK, Weisz, et al. 2015

Local Group Dwarf Galaxies at \( z \sim 7 \)

\[
\log_{10}(M_{\text{Vir}}/M_\odot) \text{ at } z \sim 7
\]

Number Density

\( z \sim 7 \)

\( 11.8 \) \( 11.0 \) \( 10.5 \) \( 9.9 \) \( 9.3 \) \( 8.7 \) \( 8.0 \) \( 7.2 \)

Less

More

\( -22 \) \( -20 \) \( -18 \) \( -16 \) \( -14 \) \( -12 \) \( -10 \) \( -8 \)

Brighter

\( M_{\text{UV}} \)

Fainter

MBK+ 2015

Required for reionization

Atek; \( \langle z \rangle = 6.26 \)

Finkelstein; \( \langle z \rangle = 6.96 \)

LMC

SMC, IC 1613

Fornax, Sagittarius

Leo I, Sculptor, Leo A

Cyn I, Draco

Leo T
The Local Group in high-z context

What did the progenitors of Local Group dwarfs look like at high redshift? How will galaxies that are observable with current and future observatories evolve to the present day?

MBK, Weisz, et al. 2015

Local Group Dwarf Galaxies at $z\sim7$

$\log_{10}(M_{\text{Vir}}/M_\odot)$ at $z\sim7$

Number Density

More

Less

$z\sim7$

HST

JWST

Required for reionization

Brighter

$M_{\text{UV}}$

Fainter

MBK+ 2015
How many MW satellites should we see based on the high-z UVLF?

Cumulative Number Number at z=0

$N(>M)_{\text{at } z=0}$

$M_{\text{UV}}$

Schechter luminosity function:
\[ \alpha = -2.03 \]

ELVIS Sim.

Garrison-Kimmel+ 2014

$M_{\text{UV}}$ at $z \sim 7$ for MW and its satellites

$M_{\text{Vir}}/M_{\odot}$ at $z \sim 7$
How many MW satellites should we see based on the high-z UVLF?

Cumulative Number at $z=0$

Factor of 10 Mismatch

$M_{\text{UV}}$

Schechter luminosity function:

$\alpha = -2.03$

ELVIS Sim.

Garrison-Kimmel+ 2014

$N(>M)$ at $z=0$

$M_{\text{vir}} [M_{\odot}]$ at $z=7$

$M_{\text{Vir}}/M_{\odot}$ at $z\sim7$
How many MW satellites should we see based on the high-z UVLF?

Factor of 10 Mismatch

Schechter luminosity function:
\[ \alpha = -2.03 \]

Garrison-Kimmel+ 2014

ELVIS Sim.

Draco

Fornax

\( M_{UV} \) at \( z \sim 7 \) for MW and its satellites

\( M_{\text{vir}} [M_\odot] \) at \( z = 7 \)

\( M_{\text{Vir}}/M_\odot \) at \( z \sim 7 \)
**How many** MW satellites should we see based on the high-z UVLF?

Some Reasons for numbers discrepancy
- Satellite destruction
- High-z UVLF Slope incorrect
- Cosmic Variance
- Completeness
- Not all halos form stars
- LG UV luminosities incorrect

...
How many MW satellites should we see based on the high-z UVLF?

Some Reasons for numbers discrepancy

- Satellite destruction
- High-z UVLF Slope incorrect
- Cosmic Variance
- Completeness
- Not all halos form stars
- LG UV luminosities incorrect
...

MBK+ 2015
**How many** MW satellites should we see based on the high-z UVLF?

**Cumulative Number Number at z=0**

- **Factor of 10 Mismatch**
  - $M_{UV}$
  - Schechter luminosity function: $\alpha = -2.03$
  - ELVIS Sim. Garrison-Kimmel+ 2014
  - Draco
  - Fornax
  - $M_{UV}$ at $z \sim 7$ for MW and its satellites

- **Broken LF slope at faint magnitudes**
  - $M_{UV}$
  - Broken luminosity function: $\alpha = -1.2$ for $M_{UV} > -13$
  - see also O’Shea+ 2015
  - Draco
  - Fornax

- **$M_{Vir}/M_\odot$ at z~7**

- **$M_{Vir} [M_\odot]$ at z=7**

- **$N(>M)$ at z=0**
How many MW satellites should we see based on the high-z UVLF?

Cumulative Number at $z=0$

Factor of 10 Mismatch

$M_{UV}$

Schechter luminosity function:

$\alpha = -2.03$

ELVIS Sim.

Garrison-Kimmel+ 2014

Broken LF slope at faint magnitudes

$M_{UV}$

broken luminosity function:

$\alpha = -1.2$ for $M_{UV} > -13$

see also O'Shea+ 2015

$N(M)$ at $z=0$

$M_{vir} [M_\odot]$ at $z=7$

$M_{vir}/M_\odot$ at $z=7$

MBK+ 2015

Changes SHM relation,
Faint galaxies live in more massive halos, ...
What did the progenitors of Local Group dwarfs look like at high redshift?

How will galaxies that are observable with current and future observatories evolve to the present day?

Simple LF modification for Local Group Dwarf Galaxies at $z \sim 7$

Steep Slope: Vastly over-predict LG galaxy counts at $z=0$

Broken Slope: match LG counts, still get reionization

$\log_{10}(M_{\text{vir}}/M_\odot)$

$\alpha = -2$

$\alpha = -1.2$

$M_{\text{UV}}$

MBK+ 2015
Conclusions

• There is a natural and fundamental connection between low-mass galaxies and cosmic reionization in all ΛCDM models

• Resolved stellar populations of nearby, faint galaxies may be the best pathway to study this connection
  - JWST unlikely to directly detect progenitors of Fornax at z~7
  - Fossil Record for hundreds of low-mass galaxies within ~5 Mpc accessible with JWST
  - Improvements in stellar models & absolute stellar ages very important

• Steep high-z UVLF slope over-predicts LG galaxy counts
  - Break in slope of -1.2 at $M_{UV}$>-13 reconciles counts, maintains reionization
  - Better understanding of completeness in LG galaxy counts
  - Important to find more Draco to Fornax mass galaxies outside LG

See poster by Andrew Graus

Fraction of dwarfs imaged below oMSTO

MW: 100%  M31: ~15%  Field: ~50%
HST Cycle 22

PI: E. Skillman
4 M31 satellites to oMSTO

PI: N. Martin
17 M31 satellites to sub-HB/oMSTO

PI: D. Weisz
PegDIG & WLM to oMSTO
Resolving the Local Volume

Projected Z distance (Mpc)

Projecting X distance (Mpc)

M81 Group

LG

NGC 253 Group

Cen A Group

Log $M_*$ (M$_\odot$)
Resolving the Local Volume

Projected Z distance (Mpc)

Projected X distance (Mpc)

M81 Group

LG

NGC 253 Group

Cen A Group

JWST MSTO limit

Log $M_\odot$
A sive discussion of several of the uncertainties discussed here. In this context, we are basing the SFH on the IMF of lower-mass stars. This assumption is crucial for accurately inferring UV luminosities at early epochs. Any bias in our calculations is therefore likely to be in the direction of underestimating the UV luminosities at early epochs.

Table 1: Stellar IMF

- We assume a fully populated Kroupa IMF, which is consistent with observational data.

Figure 3: Observed UV magnitudes with respect to $M_V(z=0)$

- The Local Group at high redshift.
- $M_{UV}(z \sim 7) = 0.71 M_V(z=0) - 2.71$

- Observed trends and their fits.
- $\sigma_{fit} = 0.46$ mag