Little Blue Dots in the Hubble Space Telescope Frontier Fields: Precursors to Globular Clusters?

Debra Meloy Elmegreen$^1$ and Bruce G. Elmegreen$^2$

$^1$ Department of Physics and Astronomy, Vassar College, Poughkeepsie, NY 12604, USA; elmegreen@vassar.edu
$^2$ IBM Research Division, T.J. Watson Research Center, 1101 Kitchawan Road, Yorktown Heights, NY 10598, USA; bge@us.ibm.com

Received 2017 November 15; revised 2017 December 6; accepted 2017 December 7; published 2017 December 21

Abstract
Galaxies with stellar masses $<10^{7.4} M_\odot$ and specific star formation rates sSFR $>10^{-7.4} \text{yr}^{-1}$ were examined on images of the Hubble Space Telescope Frontier Field Parallel for Abell 2744 and MACS J0416.1-02403. They appear as unresolved “Little Blue Dots” (LBDs). They are less massive and have higher specific star formation rates (sSFRs) than “blueberries” studied by Yang et al. and higher sSFRs than “Blue Nuggets” studied by Tacchella et al. We divided the LBDs into three redshift bins and, for each, stacked the B435, V606, and I814 images convolved to the same stellar point-spread function (PSF). Their radii were determined from PSF deconvolution to be $\sim$80 to $\sim$180 pc. The high sSFRs suggest that their entire stellar mass has formed in only 1% of the local age of the universe. The sSFRs at similar epochs in local dwarf galaxies are lower by a factor of $\sim$100. Assuming that the star formation rate is $\Sigma_{ff} M_{gas}/ff$ for efficiency $\Sigma_{ff}$, gas mass $M_{gas}$, and free-fall time, $\Sigma_{ff}$ the gas mass and gas-to-star mass ratio are determined. This ratio exceeds 1 for reasonable efficiencies, and is likely to be $\sim$5 even with a high $\Sigma_{ff}$ of 0.1. We consider whether these regions are forming today’s globular clusters. With their observed stellar masses, the maximum likely cluster mass is $\sim 10^5 M_\odot$, but if star formation continues at the current rate for $\sim 10^{11} ff$ $\sim 50$ Myr before feedback and gas exhaustion stop it, then the maximum cluster mass could become $\sim 10^6 M_\odot$.

Key words: galaxies: formation – galaxies: starburst – galaxies: star formation – globular clusters: general – stars: formation

1. Introduction

Large-scale deep surveys have recently enabled studies of smaller galaxies at higher redshifts. “Green peas” discovered from citizen science examinations (Cardamone et al. 2009) of the Sloan Digital Sky Survey (SDSS) are luminous compact low-mass ($10^8$–$10^9 M_\odot$) galaxies with high specific star formation rates (sSFRs), $\sim 10^{-8}$ yr$^{-1}$. They are thought to be local analogs of Ly$\alpha$ emitters, which are low-mass high star formation galaxies that are increasingly common at $z > 2$. Recently, a search in SDSS for even lower mass local counterparts revealed “blueberries,” which are small starburst galaxies less than 1 kpc in diameter with log(Mass) = 6.5 to 7.5; they are a faint extension of the green peas (Yang et al. 2017).

Here we report the discovery of even lower mass galaxies in the Hubble Space Telescope (HST) Frontier Fields Parallel for Abell 2744 and MACS J0416.1-2403. Their properties suggest they could be dwarf galaxies like those proposed to be the formation sites of today’s low-metallicity globular clusters (Elmegreen et al. 2012; Leaman et al. 2013). Their selection and properties are discussed in Section 2 and their implications for galaxy formation and globular clusters are in Section 3. A conclusion is in Section 4.

2. Data and Results

The Frontier Fields comprise six galaxy clusters and six corresponding parallel fields with deep HST imaging at optical (ACS camera) through near-infrared (WFC3 camera) wavelengths. Archival data of two Frontier Field Parallels, Abell 2744 and MACS J0416.1-2403, were used for this study. Abell 2744 Parallel (hereafter A2744) and MACS J0416.1-2403 Parallel (hereafter M0416) have publicly available Frontier Fields Catalogs with tabulated photometry (Merlin et al. 2016) and photometric redshifts, masses, and star formation rates (SFRs; Castellano et al. 2016). They are available through the ASTRODEEP site. There are 3411 cataloged galaxies in A2744 and 3732 in M0416. For our analysis we used images in the F435W, F606W, F814W, and F160W passbands (hereafter, B, V, I, H). The BVI images reach AB mag $\sim$29 in these two fields. They span 10,800 $\times$ 10,800 pixels; we used the mosaics with a scale of 0.03 pixel$^{-1}$.

In the ASTRODEEP composite color $BIH$ images made from $B$, $I$, and $H$ passbands, several galaxies stand out as nearly point sources that are bright blue. They appear as “Little Blue Dots” (LBDs). We sought to examine these as examples of the low-mass, high star formation end of the distribution of galaxies. From the Frontier Fields catalogs of SFR and masses, we plotted specific sSFR versus mass, shown in Figure 1. There are 546 galaxies in A2744 and 547 in M0416 that have sSFRs greater than $10^{-7.4}$; of these, 173 in A2744 and 226 in M0416 have log(Mass) between 5.8 and 7.4. We further restricted the redshift range to $0.5 < z < 5.4$, resulting in 198 galaxies in A2744 and 250 in M0416. We examined all of these galaxies in the $BIH$ color images to search for LBDs. Many were eliminated either because they were too faint to see, or were extended galaxies rather than point sources. Many others were eliminated because they appeared to be spurious sources. We found 55 LBDs, or about 12.2% of this mass, redshift, and sSFR range. Considering just the mass range, the LBDs account for 5.1% of the tabulated galaxies.

The LBD galaxies were divided into three groups according to redshift. All have log(sSFR) $> -7.4$. Group 1 has 19 galaxies with average $z = 0.7$ and average log(Mass) = 6.2,
with the names and fields indicated. The lower panel shows composite $BVI$ stacked images for each group. The stacked images appear as nearly point sources, just like the individual images.

Figure 3 shows a log–log plot of the SFR as a function of mass for all four groups of LBDs as well as for the local blueberries (from Figure 5 of Yang et al. 2017). Lines indicate a constant sSFR. The group 4 galaxies (brown dots) are part of the normal sample of galaxies in terms of their sSFRs; they are at the lower mass, higher-sSFR limit of the SDSS galaxies in Figure 5 of Yang et al. (2017). Most SDSS galaxies have log(sSFR) $= -10$, whereas group 4 is at the high end with log(sSFR) $= -9$. In contrast, the LBDs in groups 1–3 are two orders of magnitude higher in sSFRs than these, and several times higher in sSFRs than the blueberries.

Group 4 galaxies also appear as LBDs on the $B$H images, but their sSFRs are almost $2 \times$ lower than the group 1–3 galaxies. Group 4 galaxies have high SFRs, making them blue, but they have much more stellar mass than groups 1–3. This larger mass is indicated by their average $(B - H)$ color index, which is several tenths of a magnitude redder than that of groups 1–3 galaxies. Average masses and $(B - H)$ indices are listed in Table 1.

Gaussian fits were done for each stacked image in each filter for the four groups. The resulting dispersions, $\sigma$, were deconvolved from the stellar dispersions in order to get the average galaxy radii (assumed to be the half widths at half maxima, $2.35 \sigma$) in each passband. Fractional uncertainties in the deconvolved radii were determined from the quadratic sums of the fractional uncertainties in the galaxy and stellar sizes. For groups 1, 2, and 4, we used $\sigma$ from the $I$-band images because they were the highest quality. For group 3, which has the highest redshift, we used the $V$ image. The angular size was converted to linear size for each redshift using a $\Lambda$CDM model (Ade et al. 2014, $\Omega_m = 0.315$, $H = 67.3$ km s$^{-1}$ Mpc$^{-1}$). The results are in Table 1.

3. Discussion

3.1. A Recent Burst

The LBD galaxies have high sSFRs, on the order of $10^{-7}$ yr$^{-1}$. From the $\Lambda$CDM model, we determined the age of the universe corresponding to the average redshift of each LBD group, and multiplied that by the average sSFR for that group. The values in Table 2 range from $1.5 \times 10^{10}$ yr for groups 1–3, but it is only $1.4 \times 10^{9}$ for group 4. The inverse of these numbers is the fraction of the age of the universe during which the observed stellar mass has been formed at the observed SFR. The very high values suggest that star formation in group 1–3 LBDs began in the last 1% or less of the local age of the universe.

3.2. Gas Mass Estimates

We estimate the gas mass in the LBD galaxies using the usual relation for the SFR, $S$:

$$S = \epsilon_{ff} M_{gas}/t_{ff}$$

for efficiency per free-fall time $\epsilon_{ff}$ (e.g., Krumholz & McKee 2005), gas mass $M_{gas}$, and free-fall time $t_{ff} = (32G\rho/[3\pi])^{-1/2}$ for gas density $\rho = M_{gas}/(4\pi R^2/3)$; $R$ is the deconvolved radius from the stacked images. After
rearranging terms,
\[ M_{\text{gas}} = \left( \frac{\pi^2}{8G} \right)^{1/3} \frac{R(S/\epsilon_{ff})}{S^{2/3}}. \]  

(2)

Because \( \epsilon_{ff} \) is not measured, we evaluate \( M_{\text{gas}} \epsilon_{ff}^{2/3} \) from the observed quantities,
\[ M_{\text{gas}} \epsilon_{ff}^{2/3} = 6.5 \times 10^4 R \times S^{2/3} M_\odot, \]  

(3)

where now \( R \) is in parsecs and \( S \) is in \( M_\odot \) yr\(^{-1}\).

The results are in Table 2: \( \log(M_{\text{gas}} \epsilon_{ff}^{2/3}) \sim 6.7 \) for groups 1, 2, and 3, and \( \sim 6.5 \) for group 4, which are more like normal galaxies. The ratio of this efficiency-normalized gas mass to the observed stellar mass is also given, and is of the order of unity for groups 1–3.

These gas-to-star ratios are unusually high for galaxies in groups 1–3, considering that the usual Kennicutt–Schmidt relation has \( \epsilon_{ff} \sim 0.01 \), which would make the gas-to-star ratios 45, 16, and 12, respectively. Because an efficiency of \( \epsilon_{ff} \sim 1 \) is difficult to justify (i.e., it would imply that all of the gas converts to stars in one free-fall time, without feedback, low-density gas, etc.), the gas-to-star ratio is more likely \( \sim 5 \), which is what \( \epsilon_{ff} \sim 0.1 \) would give.

The sSFR in LBDs is also extreme in another sense. The inverse, \( \sim 10^7 \) years, implies that nearly all of the stars have formed within the last 10 Myr, which is too short a time for most of the massive stars to have supernovae. This suggests a high star formation efficiency and the formation of bound clusters (Parmentier & Baumgardt 2012).

### 3.3. Star Formation Histories of Local dLrrs

Star formation histories of local dwarf galaxies do not show an early phase with an SFR as high as in the LBDs, which is \( \sim 0.4 M_\odot \) yr\(^{-1}\), from the average of the log(SFR) for groups 1–3 in Table 1.

In the local dLrr WLM, the peak of the SFR 9–12 Gyr ago was \( \sim (6.7 \pm 1.5) \times 10^{-4} M_\odot \) yr\(^{-1}\) (Dolphin 2000) when the stellar mass was slightly less than in the LBDs, \( \sim 8 \times 10^9 M_\odot \) (Leaman et al. 2012). This makes log(sSFR) \( \sim -9.1 \) for SFR yr\(^{-1}\), two orders of magnitude lower than for LBDs. At the average redshift of \( z = 0.73 \) for group 1, the age of the former stars today would be 6.6 Gyr. In WLM, the SFR at around 6.6 Gyr ago was \( \sim (1.3 \pm 1.5) \times 10^{-4} M_\odot \) yr\(^{-1}\) (Dolphin 2000), and the stellar mass was \( \sim 4 \times 10^9 M_\odot \) (from an integral over the SFR), which is a similar \( M_{\text{star}} \) to that in the LBDs at that age (Table 1). However, the log(sSFR) in WLM was lower by more than three orders of magnitude, approximately \( -10.5 \) for the same units.

For the local dSph galaxy Fornax, de Boer et al. (2012a) determined an SFR that averages \( \sim (1.6 \pm 0.5) \times 10^{-3} \) between 10 and 14 Gyr ago, and builds up a stellar mass of \( 6.5 \times 10^6 M_\odot \) by the end of that time. Thus log(sSFR) \( \sim -9.6 \). At 5–10 Gyr ago, the SFR was \( (3.3 \pm 0.3) \times 10^{-3} M_\odot \) yr\(^{-1}\), and \( M_{\text{star}} \sim 1 \times 10^7 M_\odot \), so log(sSFR) \( \sim -9.5 \).

### 3.4. Globular Cluster Formation

Star-forming regions produce a fraction, \( \Gamma \), of their total stellar mass in the form of bound clusters, and these clusters form with a mass distribution function that spreads out the total into many individual clusters, most of which will not survive for a Hubble time. The mass distribution is often expressed as a Schechter function (Adamo et al. 2015) with a power-law slope of \( -2 \) (for linear intervals of mass) and an exponential drop at some high cluster mass, \( M_c \). For high SFR, \( M_c \) can be larger than \( 10^5 M_\odot \) (e.g., Zhang & Fall 1999) and the distribution function is essentially a power law up to a globular cluster mass. Considering this limit, or the case of a pure power law (Whitmore et al. 2014), integrals over the distribution function

### Table 1

| Group | No. | \( z \) | \( \log(M_{\text{Mass}}) \) \((M_\odot)\) | \( \text{Radius} \) \((\text{pc})\) | \( (B - H) \) \((\text{mag})\) | \( \log(\text{SFR}) \) \( (M_\odot \) yr\(^{-1}\)) | \( \log(\text{SFR}) \) \( (\text{yr}^{-1})\) |
|-------|-----|--------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 1     | 19  | 0.73 ± 0.11 | 6.20 ± 0.29 | 183 ± 69 | 0.16 ± 0.76 | -0.83 ± 0.29 | -7.03 ± 0.13 |
| 2     | 16  | 1.45 ± 0.28 | 6.92 ± 0.21 | 148 ± 28 | 0.55 ± 0.41 | -0.27 ± 0.28 | -7.19 ± 0.13 |
| 3     | 20  | 4.09 ± 0.86 | 6.97 ± 0.19 | 84 ± 38 | 0.69 ± 0.55 | -0.05 ± 0.21 | -7.02 ± 0.05 |
| 4     | 26  | 0.83 ± 0.09 | 7.61 ± 0.30 | 331 ± 77 | 1.02 ± 0.64 | -1.26 ± 0.33 | -8.87 ± 0.27 |
is the minimum cluster mass $M_{\text{min}} \approx 50 M_\odot$. The average for groups 1–3 is $t_{\text{ff}} \approx 5 \times 10^6$ year. If star formation continues for $\sim 10 t_{\text{ff}}$ at the average SFR of $\sim 0.4 M_\odot \text{yr}^{-1}$, then the final stellar mass in the burst will be $M_{\text{star}} \sim 2 \times 10^7 M_\odot$ and the maximum cluster mass is likely to be $5.2 \times 10^5$. If $\Gamma = 0.5$ (Adamo et al. 2011) for the SFR surface densities of LBDs, which average $\sim 16 M_\odot \text{yr}^{-1} \text{kpc}^{-2}$ for groups 1–3, then this maximum expected mass is $10^6 M_\odot$.

Zaritsky et al. (2016) examined the globular cluster number as a function of galaxy mass for local galaxies. From their Figure 4, they derived a cluster mass fraction of 0.013 for $M_{\text{star}} = 10^{8.5} M_\odot$. These globular clusters are typically older than most of a galaxy’s stars, so they were presumably present when the galaxy had only 10% of its present mass. If we consider $0.1 \times$ the present galaxy mass and $10 \times$ the present globular cluster mass to account for cluster mass loss according to current models for the origin of multiple stellar populations in these clusters (Decressin et al. 2007; D’Ercole et al. 2008; Webb & Leigh 2015), then the mass fraction in globular clusters at that early time was $0.013 \times 10/(0.013 \times 10 + 0.1) = 0.57$. Thus young versions of galaxies like these could have been dominated in mass by one or two globular clusters when the clusters formed. This situation is similar to what we may be seeing with the LBDs.
3.5. Evidence from Simulations

Cosmological simulations indicate that star-forming galaxies go through stages of compaction. Tacchella et al. (2016) found that compact high-SFR galaxies have high gas fractions with short depletion timescales; they referred to these galaxies as “blue nuggets.” Their Figure 2 shows sSFR versus mass for their proposed evolutionary sequence of high-sSFR galaxies evolving into quenched galaxies. The lower stellar mass limit in their simulations is log $M_{\star} = 7$, which is approximately the mass of an LBD galaxy. Their $z \sim 6$ galaxies that start out as low-mass, high-SFR galaxies become high-mass, low-sSFR galaxies by $z = 1$. The sSFR for the high redshift galaxies is log(sSFR/yr$^{-1}$) = −8.5. These simulated galaxies are not as extreme in sSFR as the LBDs, which at log $M_{\star} = 7$ have log(sSFR/yr$^{-1}$) = −7.

Zoom-in simulations of galaxy formation in a cosmological context were used to study cluster formation in Pfeffer et al. (2017) using a detailed sub-grid prescription. The galaxies readily formed massive clusters because of their high ambient pressures. LBDs are lower mass galaxies than they studied, but LBDs could still have relatively high pressures considering the high gas densities in Table 2. Observations of gravitationally lensed massive star-forming regions that could contain globular cluster progenitors were in Vanzella et al. (2017).

4. Conclusions

Low mass galaxies (log($M_{\star}/M_\odot$) < 7.4) with high sSFRs (log(sSFR/yr$^{-1}$) > −7.4) in two Frontier Field Parallels were examined by eye and found to have a characteristic appearance, which we have termed LBDs. A more complete survey of these fields uncovered more LBDs of higher mass. The low-mass LBDs have such high sSFRs that they appear to have formed all of their stars in the last 1% of the age of the universe for them. They appear to be gas-dominated compared to stars, perhaps by a factor of 5, and midway through the process of forming massive clusters that will eventually be the globular clusters of today. These clusters would have represented a high fraction of the stellar mass in these systems when they formed, and that high fraction is consistent with the observed mass fraction in local dwarf galaxies. We suggest that objects like this are the long-sought progenitors of low-metallicity globular clusters, which formed in dwarf galaxies and were assimilated into the halos of today’s spirals and ellipticals.

We thank Marc Rafelski for his helpful discussions about stacking images.

ORCID iDs

Debra Meloy Elmegreen  @  https://orcid.org/0000-0002-1392-3520
Bruce G. Elmegreen  @  https://orcid.org/0000-0002-1723-6330

References

Adamo, A., Knuijssen, J. M. D., Bastian, N., Silva-Villa, E., & Ryon, J. 2015, MNRAS, 452, 246
Adamo, A., Ostlin, G., & Zackrisson, E. 2011, MNRAS, 417, 1904
Ade, P. A. R., Aghanim, N., & Armitage-Caplan, C. 2014, A&A, 571, A16
Cardamone, C., Schawinski, K., Sarzi, M., et al. 2009, MNRAS, 399, 1191
Castellano, M., Amorn, R., Merlin, E., et al. 2016, A&A, 590, A31
Chandar, R., Fall, S. M., Whitmore, B. C., & Mulia, A. J. 2017, ApJ, 849, 128
de Boer, T. J. J., Tolstoy, E., Lemesle, B., et al. 2014, A&A, 572, A10
de Boer, T. J. L., & Fraser, M. 2016, A&A, 590, A35
de Boer, T. J. L., Tolstoy, E., Hill, V., et al. 2012a, A&A, 544, A73
de Boer, T. J. L., Tolstoy, E., Hill, V., et al. 2012b, A&A, 539, A103
Decressin, T., Charbonnel, C., & Meynet, G. 2007, A&A, 475, 859
D’Ercole, A., Vesperini, E., DAntona, F., McMillan, S. L. W., & Recchi, S. 2008, MNRAS, 391, 825
Dolphin, A. E. 2000, ApJ, 531, 804
Elmegreen, B. G. 2000, ApJ, 530, 277
Elmegreen, B. G., Elmegreen, D. M., Tompkins, B., & Jenkins, L. G. 2017, ApJ, 847, 14
Elmegreen, B. G., Malhotra, S., & Rhoads, J. 2012, ApJ, 757, 9
Krumholz, M. R., & McKee, C. F. 2005, ApJ, 630, 250
Leaman, R., VandenBerg, D. A., & Mendel, J. T. 2013, MNRAS, 436, 122
Leaman, R., Venn, K. A., Brooks, A. M., et al. 2012, ApJ, 750, 33
Merlin, E., Amorn, R., Castellano, M., et al. 2016, A&A, 590, A30
Parmentier, G., & Baugnardt, H. 2012, MNRAS, 427, 1940
Pfeffer, J., Knuijssen, J. M. D., Crain, R. A., & Bastian, N. 2017, MNRAS, in press (arXiv:1712.00019)
Tacchella, S., Dekel, A., Carollo, C., et al. 2016, MNRAS, 457, 2790
Vanzella, E., Calura, F., Meneghetti, M., et al. 2017, MNRAS, 467, 4304
Webb, J. J., & Leigh, N. W. C. 2015, MNRAS, 453, 3278
Whitmore, B. C., Chandar, R., Bowers, A. S., et al. 2014, AJ, 147, 78
Yang, H., Malhotra, S., Rhoads, J., & Wang, J. 2017, ApJ, 847, 38
Zaritsky, D., McCabe, K., Aravena, M., et al. 2016, ApJ, 818, 99
Zhang, Q., & Fall, S. M. 1999, ApJL, 527, L81

Table 2

| Group | Age of Univ. | log($M_{\star}/M_\odot$) | M$_{\text{gas}}^3$/M$_{\text{star}}$ | Avg. Density (atoms cm$^{-3}$) | log(t$_{\text{ff}}$) (years) |
|-------|--------------|-----------------|-----------------|-----------------|-----------------|
| 1     | 469          | 6.6             | 2.1             | 19              | 7.0             |
| 2     | 513          | 6.8             | 0.76            | 68              | 6.7             |
| 3     | 147          | 6.7             | 0.54            | 290             | 6.4             |
| 4     | 9.0          | 6.5             | 0.076           | 2.9             | 7.4             |

Derived Quantities