X-RAYS FROM BLUE COMPACT DWARF GALAXIES

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ABSTRACT

We measured the X-ray fluxes from an optically selected sample of blue compact dwarf galaxies (BCDs) with metallicities <0.07 solar and distances less than 15 Mpc. Four X-ray point sources were observed in three galaxies, with five galaxies having no detectable X-ray emission. Comparing X-ray luminosity and star formation rate (SFR), we find that the total X-ray luminosity of the sample is more than 10 times greater than expected if X-ray luminosity scales with SFR according to the relation found for normal-metallicity star-forming galaxies. However, due to the low number of sources detected, one can exclude the hypothesis that the relation of the X-ray binaries to SFR in low-metallicity BCDs is identical to that in normal galaxies only at the 96.6% confidence level. It has recently been proposed that X-ray binaries were an important source of heating and reionization of the intergalactic medium at the epoch of reionization. If BCDs are analogs to unevolved galaxies in the early universe, then enhanced X-ray binary production in BCDs would suggest an enhanced impact of X-ray binaries on the early thermal history of the universe.

Key words: galaxies: individual (blue compact dwarf) – stars: formation – X-rays: galaxies

1. INTRODUCTION

Most bright X-ray sources within galaxies are compact objects. Massive, short-lived stars (>8 M\(_\odot\)) leave behind compact objects that can form X-ray binaries, which are observed as point-like sources. X-ray radiation can be used to study the recent past’s star formation of a galaxy since a higher star formation rate (SFR) will produce larger number of massive stars. Massive stars (>8 M\(_\odot\)) with active star formation show a well-defined relation between X-ray luminosity and SFR (Kunth & Ostlin 2000; Thuan et al. 2004). We measured the X-ray fluxes from an optically selected sample of blue compact dwarf galaxies (BCDs) with metallicities <0.07 solar and distances less than 15 Mpc. Four X-ray point sources were observed in three galaxies, with five galaxies having no detectable X-ray emission. Comparing X-ray luminosity and star formation rate (SFR), we find that the total X-ray luminosity of the sample is more than 10 times greater than expected if X-ray luminosity scales with SFR according to the relation found for normal-metallicity star-forming galaxies. However, due to the low number of sources detected, one can exclude the hypothesis that the relation of the X-ray binaries to SFR in low-metallicity BCDs is identical to that in normal galaxies only at the 96.6% confidence level. It has recently been proposed that X-ray binaries were an important source of heating and reionization of the intergalactic medium at the epoch of reionization. If BCDs are analogs to unevolved galaxies in the early universe, then enhanced X-ray binary production in BCDs would suggest an enhanced impact of X-ray binaries on the early thermal history of the universe.

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2. OBSERVATIONS AND ANALYSIS

We measured the X-ray fluxes from an optically selected sample of blue compact dwarf galaxies (BCDs) with metallicities <0.07 solar and distances less than 15 Mpc. Four X-ray point sources were observed in three galaxies, with five galaxies having no detectable X-ray emission. Comparing X-ray luminosity and star formation rate (SFR), we find that the total X-ray luminosity of the sample is more than 10 times greater than expected if X-ray luminosity scales with SFR according to the relation found for normal-metallicity star-forming galaxies. However, due to the low number of sources detected, one can exclude the hypothesis that the relation of the X-ray binaries to SFR in low-metallicity BCDs is identical to that in normal galaxies only at the 96.6% confidence level. It has recently been proposed that X-ray binaries were an important source of heating and reionization of the intergalactic medium at the epoch of reionization. If BCDs are analogs to unevolved galaxies in the early universe, then enhanced X-ray binary production in BCDs would suggest an enhanced impact of X-ray binaries on the early thermal history of the universe.

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This paper reports on the relation between total X-ray luminosity and SFR for a sample of BCDs with metallicities <0.07 solar at distances less than 15 Mpc. The X-ray observations and analysis of X-ray sources within each galaxy are described in Section 2. Section 3 describes estimation of the SFR for each galaxy based on infrared, H\(_\alpha\), and far ultraviolet luminosities reported in the literature. We conclude, in Section 4, with a discussion of the results and a comparison with the X-ray versus SFR correlation found in normal-metallicity galaxies.

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source. However, the sources in DDO 68 are a small fraction of the total luminosity and our results are not significantly affected by removal of one or both or these sources. Indeed, in the discussion below we exclude these sources because they are below the luminosity threshold, $2 \times 10^{38}$ erg s$^{-1}$ in the 2–10 keV band, used in the previous studies of the relation of X-ray binary population to SFR that we use for comparison (Grimm et al. 2003; Kaaret & Alonso-Herrero 2008).

3. STAR FORMATION RATE

SFR estimates are often uncertain, so we used four methods; see Table 2. The first was to calculate SFR using 24 $\mu$m luminosities, $L(24 \mu$m), found in the literature and applying Equation (10) in Calzetti et al. (2010). Of the many SFR relations based on $L(24 \mu$m) considered by those authors, the one selected consistently gave the highest SFR. Second, we found SFR estimates in the literature based on H$\alpha$ luminosity for each galaxy, except for HS 1442+4250 where the H$\beta$ luminosity was used. Third, we used Equation (17) in Calzetti et al. (2010) which combines 24 $\mu$m and H$\alpha$ luminosity and corrects for the underestimation of SFR using $L(24 \mu$m) alone. Fourth, we used far-ultraviolet (FUV) measurements obtained with the Galaxy Evolution Explorer satellite. The FUV SFRs were taken from Lee et al. (2009), except for I Zw 18, where we used the FUV luminosity from Gil de Paz et al. (2007), and UM 461, where we used the results of Sargsyan & Weedman (2009). When necessary, observational data in the relevant papers were converted into luminosity appropriate for the distances listed in Table 1. Where multiple references exist for the same parameter, the mean was taken.

4. RESULTS

These galaxies are sufficiently small, and their SFRs are sufficiently low, that fewer than one X-ray source is expected in any individual galaxy based on the measured SFRs for the galaxies and the relation between number of sources and SFR determined by Grimm et al. (2003). Thus, we group all eight galaxies into one collection by summing their X-ray luminosities and SFRs. Figure 1 shows the relation between X-ray luminosity versus SFR. Four points are plotted, one for each total SFR found in Table 2. Grimm et al. (2003) find that the relation between X-ray luminosity and the SFR for normal-metallicity galaxies with SFR $\lesssim 4.5 M_\odot$ yr$^{-1}$ is

$$L_X = (2.6 \times 10^{39} \text{ erg s}^{-1})(\text{SFR})^{5/3}.$$  

The nonlinear form of the equation is not due to any change in the physical process involved in the interactions of SFR and

### Table 1

| Galaxy       | Distance (Mpc) | $d_{25}$ (arcsec) | AGN Prob. | Exposure (ks) | Offset (arcsec) | Counts | Flux (erg cm$^{-2}$ s$^{-1}$) | Luminosity (erg s$^{-1}$) |
|--------------|----------------|-------------------|-----------|---------------|-----------------|--------|------------------------------|----------------------------|
| UGC 4483*    | 3.2            | $34 \times 18$   | 2.2%      | 3.1           | ...             | ...    | <1.79E-14                    | <2.2E+37                   |
| VII Zw 403   | 4.3            | 24 $\times 13$   | 0.1%      | 10.2          | 14.1            | 289.9  | 1.57E-13                     | 3.46E+38                   |
| Mrk 209*     | 5.7            | 23 $\times 18$   | 0.9%      | 3.1           | ...             | ...    | <1.70E-14                    | <6.6E+37                   |
| DDO 68*      | 5.9            | 60 $\times 20$   | 8.9%      | 10.0          | ...             | ...    | 8.38E-15                     | 3.5E+37                    |
| HS 1442+4250 | 10.0           | 26 $\times 6$    | 0.8%      | 5.2           | ...             | ...    | <1.02E-14                    | <1.2E+38                   |
| 0822a+3542   | 10.9           | 9 $\times 4$     | 0.3%      | 5.1           | 20.1            | 14.9   | 7.90E-15                     | 3.3E+37                    |
| I Zw 18      | 12.6           | 11 $\times 9$    | 0.1%      | 40.1          | 0.2             | 499.3  | 6.6E-14                      | 1.2E+39                    |
| UM 461*      | 13.4           | 12 $\times 9$    | 2.1%      | 34.9          | ...             | ...    | <1.54E-15                    | <3.3E+37                   |

**Notes.** The table includes the galaxy name, distance, $d_{25}$ major and minor radii, the probability that a source at the measured flux level or upper limit is a background active galactic nucleus (AGN) taking into account the size of the detected source or the point source detection limit for a source with 10 counts, and the luminosity in the 2–10 keV band. The names of detected sources are. a CXOU J112803.0+785953, b CXOU J095646.0+224929, c CXOU J095645.7+284920, d CXOU J093401.9+551428. Galaxies with an asterisk (*) were observed specifically for this study.

### Table 2

| Galaxy       | SFR (24 $\mu$m) (10$^{-3} M_\odot$ yr$^{-1}$) | SFR (H$\alpha$) (24 $\mu$m) (10$^{-3} M_\odot$ yr$^{-1}$) | SFR (H$\alpha$) (24 $\mu$m) (10$^{-3} M_\odot$ yr$^{-1}$) | SFR (FUV) (10$^{-3} M_\odot$ yr$^{-1}$) | $L_X$ (2–10 keV) (10$^{37}$ erg s$^{-1}$) |
|--------------|---------------------------------------------|---------------------------------------------------------|---------------------------------------------|-------------------------------------|-------------------------------------|
| UGC 4483b,d  | 1.0                                         | 2.2                                                     | 2.7                                         | 3.9                                 | <2.1                                 |
| VII Zw 403b,c,d,g | 7.5                                         | 12.0                                                    | 13.0                                        | 12.0                                | 34.6                                 |
| Mrk 209b,c,d,j | 16.0                                        | 36.0                                                    | 41.0                                        | 20.0                                | <10.0                                |
| DDO 68b,c,d   | <2.4                                        | <1.7                                                    | 1.5                                         | 23.4                                | 6.8                                  |
| HS 1442+4250b,h | 7.0                                         | 11.0                                                    | 10.0                                        | 21.4                                | <13.7                                |
| 0822a+3542c,f,l | 3.7                                         | 6.4                                                     | 5.5                                         | 2.9                                 | <11.0                                |
| I Zw 18b,c,d | 9.4                                         | 28.0                                                    | 19.0                                        | 44.2                                | 126.3                                |
| UM 461b,c,l,m | 38.0                                        | 54.0                                                    | 66.0                                        | 8.3                                 | <6.0                                  |
| Total        | 85.0                                        | 141.3                                                   | 158.7                                       | 136.1                               | 167.7                                 |

**Notes.** References for H$\alpha$ and 24 $\mu$m data: a Dale et al. (2009), b Engelbracht et al. (2008), c Hunter & Elmegreen (2004), d Hunter et al. (2010), e Kennicutt et al. (2008), f Kewley et al. (2007), g Lynds et al. (1998), h Popescu et al. (1999), i Relano et al. (2007), j Schulte-Ladbeck et al. (2001), k Telles et al. (2001), l van Zee et al. (1998), m Wu et al. (2008).
X-ray luminosities. Instead, it is due to the statistical properties of the small number of sources in galaxies with low SFRs (Gilfanov et al. 2004). This relation is superposed on Figure 1. The X-ray luminosity measurements of Grimm et al. (2003) include point sources with luminosities down to $2 \times 10^{38} \text{ erg s}^{-1}$, thus, we have included only X-ray sources brighter than this in our total X-ray luminosity estimate of $1.6 \times 10^{38} \text{ erg s}^{-1}$.

The X-ray luminosity of the BCDs lies significantly above what would be predicted based on the known relation for normal-metallicity galaxies. Taking the highest estimate of the SFR, that derived from Hα, we find that the measured X-ray luminosity is $13 \times$ that calculated from the previous equation. We note that a linear extrapolation of the X-ray luminosity versus SFR measured at high SFR by Grimm et al. (2003) is nearly consistent with our results; this is shown as a dashed line in Figure 1. However, the nonlinear turnover at low SFR, and thus low numbers of X-ray sources, is a direct result of the application of Poisson statistics to the measured power-law distribution of source luminosities. If the true relation is linear at low SFR, this would require that either the X-ray source populations do not obey Poisson statistics or the luminosity distribution function for low-SFR galaxies differs significantly than that measured for high-SFR galaxies. Ranalli et al. (2003) and Kaaret & Alonso-Herrero (2008) found a lower ratio of X-ray luminosity to SFR, at high SFR, than did Grimm et al. (2003). This would further increase the discrepancy assuming that the reduction is applied to the nonlinear curve of Grimm et al. (2003) valid at low SFR.


given a mean of 0.286, the probability to observe two or more sources is 3.4%. Thus, one can exclude the hypothesis that the relation of the X-ray binaries to SFR in low-metallicity BCDs is identical to that in normal galaxies only at the 96.6% confidence level. Observations of a larger sample of low-metallicity BCDs is needed to test this hypothesis further.

Different SFR rate indicators are sensitive to star formation on different timescales. Hα is produced by ionizing photons from hot, massive, and short-lived stars and traces the last 10^6 years of star formation. In contrast, infrared radiation is emission from dust heated by stars of a range of masses and averages roughly the past 10^8 years of star formation. The “light-up” times for high-mass X-ray binaries (HMXBs) are of order 10^7, corresponding to the lifetimes of the progenitor stars. In a study of H II galaxies that host young and intense star formation, Rosa González et al. (2009) found that the X-ray luminosity correlated with SFR according to the relation of Ranalli et al. (2003) if the SFR was inferred from the IR luminosity. In contrast, there was a deficit in the X-ray luminosity (in the 2–10 keV band) if Hα was used as the SFR indicator. In the H II galaxy sample, the Hα SFRs are much larger than the IR SFRs and signify a young and intense star formation event. This lack of hard X-rays is expected since the starbursts are younger than the time needed for HMXB formation. In our sample of BCDs, the Hα SFRs are also larger than the IR SFRs, although by not as large a factor. This suggests that the starburst is young, although perhaps not as young as in the H II galaxies. Using the IR SFR increases the discrepancy between the measured X-ray luminosity and that inferred based on the SFR. The predicted number of X-ray sources is then 0.153 and the probability of observing two sources is 1.1%.

Lee et al. (2009) found that Hα tends to underpredict the SFR when compared with FUV estimates. They find that the ratio is a factor of two by SFR ~ 0.003 $M_\odot \text{ yr}^{-1}$, around the range of the lowest SFR galaxies considered here. We examined the FUV SFR for our sample of BCDs and find that it is slightly lower than the Hα SFR. Thus, the effect found by Lee et al. (2009) does not explain the overproduction of X-ray binaries in BCDs.

Mirabel et al. (2011) have recently proposed that HMXBs in star-forming galaxies were an important source of heating and reionization of the intergalactic medium at the epoch of reionization. If BCDs are analogous to the unevolved galaxies in the early universe, then enhanced X-ray binary production in BCDs would suggest an enhanced impact of X-ray binaries on the early thermal history of the universe over that predicted using X-ray versus SFR relations determined using near-solar-metallicity galaxies.

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