THE ASTROPHYSICAL JOURNAL, 613:L5–L8, 2004 September 20

CHANDRA CONSTRAINTS ON THE ACTIVE GALACTIC NUCLEUS FRACTION AND STAR FORMATION RATE OF RED $z \gtrsim 2$ GALAXIES IN THE FIRES MS 1054−03 FIELD

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Received 2004 June 16; accepted 2004 August 5; published 2004 August 13

ABSTRACT

Very deep near-infrared observations in the Faint InfraRed Extragalactic Survey (FIRES) have recently uncovered a significant population of red galaxies at redshifts $z > 2$. These distant red galaxies (DRGs) are efficiently selected by the criterion $J_s - K_s > 2.3$. We use *Chandra* data to examine the X-ray emission from DRGs in the $5' \times 5'$ FIRES MS 1054−03 field. Two of 40 DRGs with $K_s < 22$ are detected by *Chandra*, and we infer that 5^{+3}_{-2}% of DRGs host active nuclei with $L_X > 1.2 \times 10^{43}$ ergs s^{-1}. This fraction is smaller than that inferred from optical and near-IR spectroscopy, probably largely owing to strong spectroscopic selection biases. By stacking all undetected DRGs, we find that their average X-ray flux in the 0.5–8 keV band is $\approx 4.6 \times 10^{-17}$ ergs s^{-1} cm^{-2}. The detection is only significant in the soft (0.5–2 keV; 3.4 σ) and full (0.5–8 keV; 3.2 σ) energy bands. The mean detection may result from star formation, the presence of low-luminosity active galactic nuclei (AGNs), or a combination of both. Assuming the detection is due exclusively to star formation, we find an average instantaneous star formation rate of 214 ± 68(random) ± 73(systematic) $M_\odot$ yr^{-1}, in excellent agreement with previous results from spectral energy distribution fitting when constant star formation histories are assumed. These results may imply that DRGs contribute significantly to the cosmic star formation rate at $z \approx 2.5$. However, the mean X-ray flux strictly provides only an upper limit to the star formation rate owing to the uncertain contribution of low-luminosity, possibly obscured AGNs. Observations at other wavelengths are needed to provide independent estimates of the star formation rate of DRGs.

Subject headings: cosmology: observations — galaxies: evolution — galaxies: formation

1. INTRODUCTION

Recent studies have demonstrated that galaxies at $z > 2$ can be efficiently selected by the simple observed near-infrared (NIR) color criterion $J_s - K_s > 2.3$ (Franx et al. 2003; van Dokkum et al. 2003). These distant red galaxies (DRGs) are typically very faint in the rest-frame ultraviolet (UV) and are complementary to the UV-selected Lyman break galaxies (LBGs). Studies of their broadband spectral energy distributions (SEDs; Förster Schreiber et al. 2004) and their rest-frame optical emission lines (van Dokkum et al. 2004) indicate that at a given rest-frame optical luminosity DRGs are dustier, more massive, and have higher ages than LBGs. Their star formation rates are quite uncertain, as they depend on the assumed star formation histories: median values for DRGs with $K < 21.7$ range from ~170 $M_\odot$ yr^{-1} for constant star formation histories to ~23 $M_\odot$ yr^{-1} for declining models (Förster Schreiber et al. 2004).

In this Letter, we study the X-ray emission from DRGs, using *Chandra* observations of the field centered on the foreground cluster MS 1054−03 at $z = 0.83$. This field is one of the two Faint InfraRed Extragalactic Survey (FIRES) fields, and its population of red $z > 2$ galaxies has been described by van Dokkum et al. (2003, 2004) and Förster Schreiber et al. (2004). The X-ray properties provide information on the fraction of active galactic nuclei (AGNs) among DRGs. Spectroscopy indicates that this fraction could be substantial (van Dokkum et al. 2003, 2004), but this interpretation is uncertain because current spectroscopic samples are very incomplete. Furthermore, the stacked X-ray flux of undetected sources provides an additional constraint on the average instantaneous star formation rate. Where needed, we assume $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 70$ km s^{-1} Mpc^{-1}. Galaxy identifications refer to the N. M. Förster Schreiber et al. (2004, in preparation) FIRES catalog of the MS 1054−03 field, which includes photometric redshifts for all sources.

2. OBSERVATIONS AND SAMPLE SELECTION

The X-ray data were obtained from an archival 91 ks exposure with the *Chandra* ACIS-S3 detector. The data were obtained by the ACIS GTO team to study the foreground cluster (Jeltema et al. 2001). The reduction of the data and an analysis of the point sources in the field are presented in Johnson et al. (2003). After removal of periods with strong background flaring, the effective exposure time is 74 ks. Images of the full energy band (0.5–8 keV) were made as well as of the soft (0.5–2 keV) and hard (2–8 keV) bands.

The DRGs were selected from the $5' \times 5'$ area imaged with the Very Large Telescope (VLT) Infrared Spectrograph and Array Camera in the J_s, H, and K_s bands as part of the FIRES project. *Hubble Space Telescope* (*HST*) WFPC2 data is available in the V_{606} and I_{814} bands as well as VLT FORS1 data in the Bessel U, B, and V bands. The reduction, source detection, and photometry are described in N. M. Förster Schreiber et al. (2004, in preparation). There are 45 sources with $J_s - K_s \geq 2.3$, $K_s \leq 22$, and photometric weights (i.e., the fraction of the maximal exposure time spent on-source) in J_s and K_s greater than 0.1. Figure 1 shows the selection limits. From this group, we removed two sources because they have photometric redshifts $z < 1.8$, and three sources within ~1′ of the center of the cluster, to minimize effects of the diffuse cluster light. The final sample thus consists of 40 DRGs.

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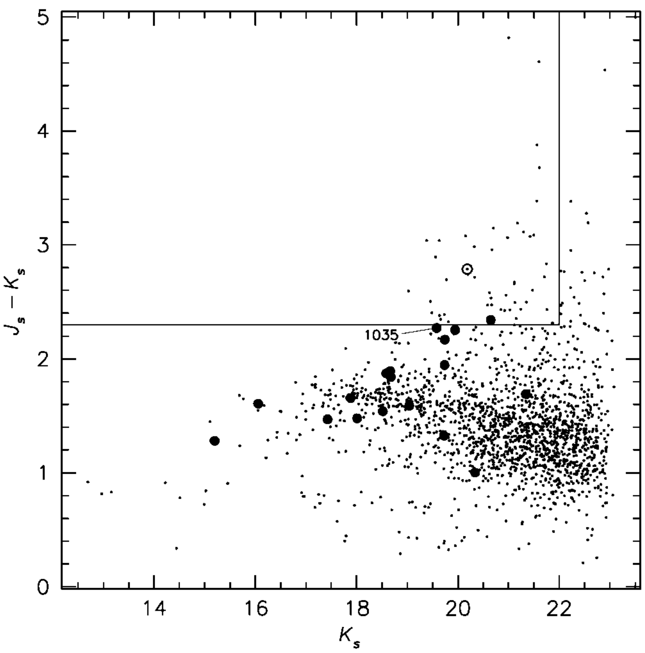

FIG. 1.—Color-magnitude diagram for all objects in the VLT field. *Chandra* point sources from Johnson et al. (2003) are shown as filled circles. The open circle shows object 313, which is a 4.7 σ detection. Our selection criteria are shown with lines. The fraction of *Chandra* sources among galaxies with $J_s - K_s > 2.3$ and $K_s < 22$ is 5%.

3. DIRECT DETECTIONS: AGN FRACTION

Johnson et al. (2003) selected point sources in the MS 1054−03 field using WAVDETECT with a rather conservative threshold (giving approximately one spurious source over the entire field), and we first determined the overlap between DRGs at $K_s < 22$ and X-ray sources in the Johnson et al. catalog (large filled circles in Fig. 1). Only one DRG (object 1100; $z_{\rm phot} = 2.9$; $K_s = 20.7$) was found to contain an X-ray source identified by Johnson et al. (object 30 in their catalog).

Next we examined the prevalence of X-ray sources fainter than the conservative limits imposed by Johnson et al. (2003). The X-ray fluxes were determined using apertures of 4″ diameter, which contain ≳70% of the flux for point sources over our entire 5′ × 5′ FIRES field.[5] For each DRG, a local background was determined from the mean flux in 30 randomly placed apertures near the location of the DRG. The locations of these apertures were constrained to be nonoverlapping, at a distance of 7″–20″ from the DRG, and at least 4″.5 from point sources identified by Johnson et al. In addition to galaxy 1100, we find one other object (313; $z_{\rm phot} = 2.0$; $K_s = 20.2$) with a significant (≈4.7 σ) X-ray flux.

The SEDs of both objects are shown in Fig. 2, along with the median SED of all other DRGs (in the observed frame; for rest-frame SEDs, see Förster Schreiber et al. 2004). The SED of object 313 is very similar to the median, suggesting that the AGN does not contribute significantly to the continuum flux. However, galaxy 1100 has much bluer optical-NIR colors than the majority of DRGs, indicating that its active nucleus may affect the SED, in particular in the rest-frame UV.

The 4 σ limit of 5.3 counts (after background subtraction) corresponds to an X-ray flux of 3.7×10^{-16} ergs s^{-1} cm^{-2} (see below) and a K-corrected luminosity of 1.2×10^{43} ergs s^{-1} in the rest-frame 2–10 keV band for the median $\langle z_{\rm phot}\rangle = 2.4$ of the DRGs in our sample. We conclude that the fraction of AGNs with $L_{\rm X} > 1.2 \times 10^{43}$ ergs s^{-1} among DRGs is 5^{+3}_{-2}% (assuming Poisson statistics).

[5] See http://cxc.harvard.edu/cal/Acis/Cal_prods/psf/Memo/s8.html.

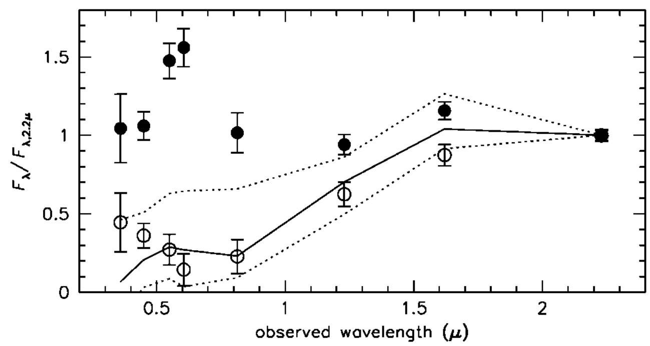

FIG. 2.—SEDs of the two DRGs associated with X-ray sources of $L_{\rm X} > 1.2 \times 10^{43}$ ergs s^{-1}. The solid line shows the median SED of all DRGs; dotted lines show the 25th and 75th percentiles of the distribution. The SED of 313 (*open circles*) is very similar to those of other DRGs, but the SED of 1100 (*filled circles*) is likely affected by emission from the nucleus, in particular in the UV.

We note here that both *spectroscopically* identified AGNs in the MS 1054−03 field have dropped out of the DRG sample after recalibration of their photometry (see van Dokkum et al. 2004). Interestingly, only one of the two (object 1035, with $J_s - K_s = 2.27$; labeled in Fig. 1) is detected with *Chandra*, suggesting that a multiwavelength approach is necessary to accurately determine the AGN fraction among red galaxies at $z > 2$.

4. STACKED EMISSION OF NONDETECTIONS

The low X-ray background allows very efficient stacking analyses of sources that individually are too faint to be detected (e.g., Alexander et al. 2003; Brandt et al. 2001; Malhotra et al. 2003; Reddy & Steidel 2004). We averaged the 38 flux measurements of the undetected DRGs, effectively increasing the exposure time to 2.8 Ms. We also averaged each of the 30 sets of background measurements. These 30 random stacks have the same properties (background and point-spread function) as the red galaxy stack and are used to assess the significance of the flux in the averaged red galaxy apertures.

The results are listed in Table 1. The average background and significance in each band was determined in the following way. Each of the 30 sets of random apertures was averaged in the same way as the DRG apertures, providing 30 independent measurements of the mean of 38 random apertures. The mean of these 30 measurements gives the background value, and their rms is used to calculate the significance of the mean detection. After background subtraction, the mean emission from DRGs

TABLE 1
STACKED X-RAY EMISSION OF DRGS

Band	Source	2″	3″	4″	6″
Soft (0.5–2 keV)	$J - K$	0.36	0.76	1.13	2.05
	Background	0.18	0.41	0.72	1.62
	rms	0.07	0.11	0.12	0.19
Hard (2–8 keV)	$J - K$	0.33	0.72	1.18	2.55
	Background	0.26	0.61	1.04	2.37
	rms	0.06	0.09	0.14	0.22
Full (0.5–8 keV)	$J - K$	0.68	1.48	2.30	4.60
	Background	0.43	1.02	1.76	3.99
	rms	0.09	0.14	0.17	0.28

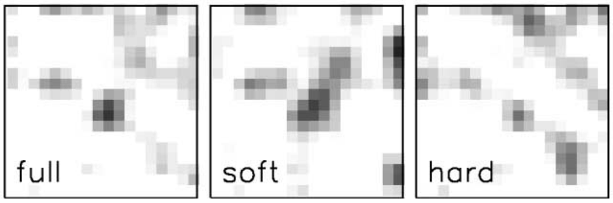

FIG. 3.—Stacked images of DRGs in the full (0.5–8 keV), soft (0.5–2 keV), and hard (2–8 keV) bands. The size of each image is $10'' \times 10''$. The DRGs are detected in the soft (3.4 σ) and full bands (3.2 σ). The detection in the hard band is not significant.

is 0.54 counts (3.2 σ significance) in the full band, 0.41 counts (3.4 σ) in the soft band, and 0.14 counts (1 σ) in the hard band. Images of the average detections are shown in Fig. 3.

A concern is that the mean flux is dominated by one or two luminous sources that are just below the detection threshold. Figure 4 shows the distribution of the X-ray fluxes of our undetected DRG sample after background subtraction as well as the average distribution of the 30 random samples. The DRGs show a tail of positive fluctuations and a deficit of negative fluctuations, consistent with the hypothesis that most sources contribute to the mean detection.

We empirically test how much flux is lost by our adopted $4''$ apertures by repeating our measurements of the mean X-ray emission using differently sized apertures. The results are listed in Table 1. As expected, the flux is a function of aperture size. Based on the values in Table 1 and the ACIS documentation, we estimate that the $4''$ apertures miss 30% $\pm$ 10% of the flux at the average location of the DRGs (~$2'.5$ from the optical axis). This aperture effect is partially countered by weak lensing of the background DRGs by the foreground $z = 0.83$ cluster. This effect is ≈15% on average (see Förster Schreiber et al. 2004). The aperture- and lensing-corrected mean flux of the DRGs is 0.66 ± 0.21(random) $\pm$ 0.11(systematic) counts in the full band. The systematic error reflects the uncertainties in the two corrections.

The average X-ray detection of the DRGs provides a constraint on their instantaneous star formation rate. In general, X-ray emission of galaxies is due to a combination of hot gas (e.g., from supernova bubbles and winds), low-mass X-ray binaries, high-mass X-ray binaries (HMXBs), and possibly an active nucleus. HMXBs are short-lived as they trace the prompt formation rate of massive stars with $M_* \sim 8\ M_\odot$, and it appears that for galaxies with star formation rates in excess of ~5 $M_\odot$ yr^{-1} they dominate the X-ray luminosity, particularly above 2 keV (Grimm et al. 2003). Several recent studies have therefore explored the relation between the instantaneous star formation rate and the rest-frame 2–10 keV X-ray luminosity (e.g., Ranalli et al. 2003; Grimm et al. 2003). Here we use the Grimm et al. (2003) relation, $\mathrm{SFR} \approx 1.49 \times 10^{-40} \times L_{2-10\,\mathrm{keV}}$. The Grimm et al. calibration gives ~30% lower star formation rates than the Ranalli et al. calibration.

We convert the observed counts in the 0.5–8 keV energy band to a rest-frame 2–10 keV luminosity in the following way. First we determined the average conversion from counts to flux from the sources listed in Johnson et al. (2003). The conversion varies by less than 10% over the ACIS field. Their conversion assumes a spectrum with photon index $\Gamma = 1.7$, and we use the Portable Interactive Multi-Mission Simulator (PIMMS) to calculate the effect of changing Γ from 1.7 to 2.0, which is the appropriate value for the greater than 2 keV spectrum of HMXBs. Applying this ≈15% correction to the empirically determined conversion

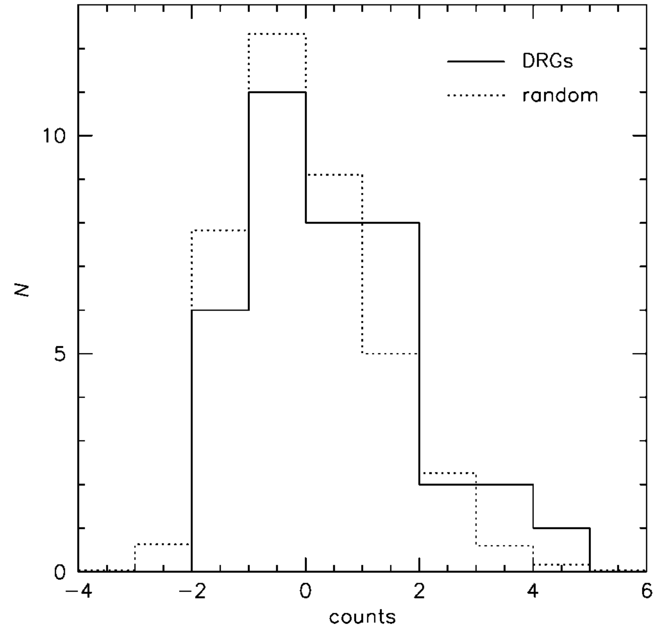

FIG. 4.—Distribution of X-ray emission among red galaxies (*solid line*) and the average histogram for the random samples (*dotted line*), after background subtraction. Compared to the random apertures, the DRGs show a deficit of negative fluctuations and an excess of positive fluctuations.

factor, we obtain $F_\mathrm{X}(0.5\text{–}8\ \mathrm{keV}) = 6.97 \times \mathrm{counts}(0.5\text{–}8\ \mathrm{keV})$, with F_X in units of 10^{-17} ergs s^{-1} cm^{-2}. The lensing- and aperture-corrected mean DRG flux is then 4.6×10^{-17} ergs s^{-1} cm^{-2} in the 0.5–8 keV band. Next, the flux is K-corrected to the rest-frame 2–10 keV band (again assuming $\Gamma = 2.0$), using $z = 2.4$. Converting the rest-frame flux to a rest-frame luminosity (for $z = 2.4$), we find $L_\mathrm{X} = 1.4 \times 10^{42}$ ergs s^{-1}, and the Grimm et al. (2003) calibration gives an instantaneous star formation rate of 214 ± 68(random) $\pm$ 73(systematic) $M_\odot$ yr^{-1}. The systematic error is due to uncertainties in the aperture and lensing correction, uncertainties in the conversion of X-ray luminosity to star formation rate, and the scatter in the relation between X-ray luminosity and star formation rate. It was assumed that these uncertainties can be added in quadrature. We note that PIMMS predicts an ~4 : 1 ratio for the soft versus hard band counts, consistent with our nondetection in the hard band.

5. DISCUSSION

Our estimate of the star formation rate in DRGs based on X-ray emission can be compared to previous estimates based on SED fitting and emission lines (van Dokkum et al. 2004; Förster Schreiber et al. 2004). The main uncertainty in the SED fits is the assumed star formation history. Förster Schreiber et al. (2004) find a median (mean) instantaneous star formation rate of 170 (190) $M_\odot$ yr^{-1} for DRGs with $K_s < 21.7$ in the MS 1054−03 field assuming continuous star formation models and only 23 (69) $M_\odot$ yr^{-1} for declining models with $\tau = 300$ Myr. As shown in van Dokkum et al. (2004), the inclusion of Hα measurements does not break the degeneracy between star formation history, dust, and instantaneous star formation rate. Our result is in excellent agreement with the high star formation rates derived from continuous (dusty) models and may imply that DRGs contribute significantly to the cosmic star formation rate at $z \approx 2.5$.

It is also interesting to compare the mean X-ray luminosity of DRGs with that of LBGs. Reddy & Steidel (2004) find a mean X-ray flux of $\sim 5 \times 10^{-18}$ ergs s^{-1} cm^{-2} in the 0.5–2 keV band and an implied star formation rate of 47 $M_\odot$ yr^{-1} for LBGs at $2 < z < 2.5$ in the Chandra Deep Field–North. As the redshift range of these LBGs and our DRGs is roughly similar, we can compare the fluxes directly, limiting systematic uncertainties. The mean flux of the DRGs is 2.3×10^{-17} ergs s^{-1} cm^{-2} in the 0.5–2 keV band, a factor of $\sim$5 higher than that of LBGs. The interpretation is unclear, as the two samples have not been matched in observed *K* magnitude, their luminosity functions may be different, and the space density of DRGs is still uncertain.

Our estimate does not include one significant systematic uncertainty, likely to be present in most attempts to infer high-redshift star formation rates from X-ray luminosities. For nearby galaxies, the angular resolution of *Chandra* can be used to subtract out the possible contamination from a central active nucleus, but this is not possible for high-redshift objects. All the X-ray luminosity attributed to HMXBs could in fact come from a population of low-luminosity AGNs. Since we do not have optical spectra for most of our objects and we do not have the X-ray counts and count rates to impose constraints based on X-ray spectral and variability information, we cannot directly rule this possibility out.

As a general caution, we remark that even if we did have optical spectra, it might be quite difficult to rule out the presence of a low-luminosity AGN. If we assume that the relation between the mass of a galaxy bulge and the mass of the bulge's central black hole (Ferrarese & Merritt 2000; Gebhardt et al. 2000) is already established for these objects, then the red galaxies in our sample have typical black hole masses $\sim 10^8\ M_\odot$. The mean X-ray luminosity of $\sim 10^{42}$ ergs s^{-1} is a factor of $\sim$100 below the typical X-ray luminosity for unobscured AGNs with similar black hole masses; i.e., the nuclei of these galaxies are heavily obscured or the possible black holes in these galaxies are accreting at low, sub-Eddington rates. In either case, if one does not have the angular resolution to separate out the nucleus, the starlight from the bulge can completely dominate the AGN light (e.g., Moran et al. 2002). The lack of obvious AGN features in a spectrum is thus not conclusive evidence against an AGN contribution if the aperture used contains most of the galaxy and the signal-to-noise ratio of the spectrum is low. A better (but still circumstantial) argument that the X-ray luminosity represents star formation might instead be the concordance of several independent star formation indicators, e.g., between the radio, dereddened UV, and X-ray in Reddy & Steidel (2004). Further independent constraints on the star formation rate in DRGs are thus urgently needed.

Studies of larger samples will provide a better measurement of the number of *luminous* AGNs: whereas our initial spectroscopy indicates AGN fractions of 30%–50% (van Dokkum et al. 2003, 2004), the *Chandra* data suggest that this is largely due to the strong spectroscopic selection bias toward galaxies with bright emission lines. It is also important to directly assess the effect of AGNs on the broadband SEDs (and hence estimates of star formation rates, ages, and dust content). Planned observations with the Near-Infrared Camera and Multi-Object Spectrometer and the Advanced Camera for Surveys on *HST* of MS 1054−03 will provide constraints on the point-source contribution to the continuum from the rest-frame UV to the optical. Finally, deeper X-ray observations are needed to further constrain the hardness ratio of the mean detection and to detect more individual X-ray sources; our results and those of Barger et al. (2003) suggest that in 1–2 Ms exposures many of the $z > 2$ red galaxies may be (faint) *Chandra* sources.

We thank the anonymous referee for comments that improved the clarity of this Letter. Support from *Chandra X-Ray Observatory* award AR4-5011X is gratefully acknowledged.

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