An X-ray detection of star formation in a highly magnified giant arc

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In the past decade, our understanding of how stars and galaxies formed during the first 5 billion years after the Big Bang has been revolutionized by observations that leverage gravitational lensing by intervening masses, which act as natural cosmic telescopes to magnify background sources. Previous studies have harnessed this effect to probe the distant Universe at ultraviolet, optical, infrared and millimetre wavelengths1–5. However, strong-lensing studies of young, star-forming galaxies have never extended into X-ray wavelengths, which uniquely trace high-energy phenomena. Here, we report an X-ray detection of star formation in a highly magnified, strongly lensed galaxy. This lensed galaxy, seen during the first third of the history of the Universe, is a low-mass, low-metallicity starburst with elevated X-ray emission, and is a likely analogue to the first generation of galaxies. Our measurements yield insight into the role that X-ray emission from stellar populations in the first generation of galaxies may play in reionizing the Universe. This observation paves the way for future strong-lensing-assisted X-ray studies of distant galaxies reaching orders of magnitude below the detection limits of current deep fields, and previews the depths that will be attainable with future X-ray observatories.

The massive galaxy cluster, SPT-CLJ2344-4243 (the Phoenix cluster), acts as a gravitational lens, magnifying our view of a background star-forming galaxy. The background galaxy is at a redshift \( z = 1.5244 \), such that we are observing it at a cosmic age of 4.2 billion years after the Big Bang (using the current Planck cosmological parameter values6 for the Hubble constant, \( H_0 = 67.4\, \text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1} \), the matter density, \( \Omega_m = 0.315 \), and density of vacuum energy, \( \Omega_k = 0.685 \)). The foreground lens, SPT-CLJ2344-4243, was discovered in a milliarcsecond-wave survey of 2,500 deg\(^2\) of the southern sky by the South Pole Telescope (SPT)4, has a measured redshift of \( z = 0.596 \), and has a dense core that likely contributes to its efficacy as a natural gravitational telescope. The highly magnified, lensed galaxy was discovered serendipitously in optical imaging data, where it appears as a thin giant arc extending approximately 12 arcsec (\( ^\circ \)) across the sky. Using follow-up optical imaging from the Hubble Space Telescope, we confirmed that the giant arc is formed by gravitational lensing of a faint star-forming background galaxy. Remarkably, a deep (~600 kilosecond (ks)) observation taken with the Chandra X-ray Observatory for the purpose of measuring the X-ray emission from SPT-CLJ2344-4243 also revealed the presence of X-ray emission from each pair of merging images that make up the giant arc (Fig. 1). We model and subtract the spatially extended foreground X-ray emission from the cluster, resulting in 30.6 ± 6.3 net, background-subtracted X-ray counts from the giant arc in the 0.5–7 keV band, and a 5.3σ detection significance.

We obtained near-infrared (NIR) spectra at three different positions along the X-ray-emitting arc with the Folded-port InfraRed Echellette (FIRE) instrument on the Magellan-I telescope; these spectra indicate the presence of multiple rest-frame optical nebular emission lines at a redshift of \( z = 1.5244 \). The similarity of the spectra taken at different positions along the arc confirm that the arc consists of two merging images with mirror symmetry. The lensed galaxy spectrum contains strong optical emission lines from a variety of different elements and ions (\( \text{H}_\alpha, \text{H}_\beta, [\text{O}\,\text{III}], [\text{O}\,\text{I}] \) and \([\text{N}\,\text{II}]\)). The relative strengths of these lines reveal the physical properties of the ionized nebular gas in the lensed galaxy13,14. In particular, the \([\text{N}\,\text{II}]/\text{H}_\alpha\) and \([\text{O}\,\text{III}]/\text{H}_\beta\) ratios are typical of those observed in star-forming galaxies and appear inconsistent with the expectations for an active galactic nucleus (AGN), and hence demonstrate that the observed X-ray emission is from ongoing star formation (see Methods for more details).

Having confirmed that the giant arc is a single strongly lensed star-forming galaxy, we created a model reconstruction of the gravitational lensing due to the massive galaxy cluster. FIRE spectra of seven multiply-imaged, lensed background galaxies with images extending from the cluster core to beyond the giant arc, along with

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the giant arc itself, robustly constrain the model (see Methods). From the lens model, the best-fit magnification of the giant arc is 65 ± 20. We also use the lens model to reconstruct de-lensed images of the giant arc in the source plane, and find that the source is an irregular blue galaxy composed of two star-forming clumps, each less than a kiloparsec in diameter, of similar brightness at ~1,900 Å in the rest frame and separated by ~500 pc in projection. The X-ray emission from the giant arc is associated with one of the two star-forming clumps, which is consistent with optical imaging of the lensing galaxy cluster in a false-colour image at optical wavelengths. The lensing geometry of the giant arc is such that the source is an irregular blue galaxy composed of two star-forming clumps, each of which colapse into a black hole or neutron star, it can accrete material from the companion massive star in what is called a high-mass X-ray binary (HMXB). Star-forming galaxies dominated by young (age <30 Myr-old) stellar populations is1, suggesting that the X-ray-emitting UV-bright clump in this lensed galaxy is most likely an extremely young star-forming region.

We measured the lensed galaxy to have a star-formation rate (SFR) between SFR = 0.8–3.3 M⊙ yr−1 using Hα emission and accounting for potential extinction due to intervening dust. We also placed an upper limit on the stellar mass of the galaxy M∗ <1.0 × 10^9 M⊙, using rest-frame NIR photometry. The SFR and mass constraints imply a specific star-formation rate (sSFR) >8 × 10^−4 yr−1, confirming the lensed galaxy to be a typical low-mass (dwarf) star-forming galaxy, with its luminosity likely dominated by young stars. All measured properties of the giant arc are given in Table 1. The only X-ray detections to date of star formation in individual galaxies are either in the local Universe18-20 or in the deepest X-ray deep fields18-20. Blind stacking analyses of large samples of galaxies21,22 have also yielded relatively low signal-to-noise measurements of the average X-ray emission from galaxies in broad redshift bins out to z ~ 5. The X-ray arc in SPT-CLJ2344-4243 is among the most distant individual galaxies in which ongoing star formation has been detected in X-rays. This X-ray-detected giant arc is much fainter than the few detections at comparable redshifts, with an intrinsic X-ray luminosity that is more than an order of magnitude below the typical z > 1.5 galaxies with X-rays detected in deep fields (Fig. 2).

High-SFR galaxies contain young stellar populations, with emission dominated by hot, massive stars. X-ray observations can directly detect the subset of these massive stars that are formed in gravitationally bound binaries23,24: when one star in the binary pair collapses into a black hole or neutron star, it can accrete material from the companion massive star in what is called a high-mass X-ray binary (HMXB). Local studies point to a correlation between Lx and SFR that reflects the direct physical relationship between the rate at which a galaxy is forming stars and the resulting population of HMXBs23,24. Star-forming galaxies dominated by young (age <30 Myr), low-metallicity stellar populations (that is, analogues of Lyman break galaxies and ‘Green Pea’ galaxies) follow a different scaling relation, and have larger Lx at a given SFR14,15,17,21,25. The X-ray-emitting lensed galaxy in SPT-CLJ2344-4243 has observed properties that reflect the fact that this source is among the most distant individual galaxies in which ongoing star formation has been detected in X-rays. This X-ray-detected giant arc is much fainter than the few detections at comparable redshifts, with an intrinsic X-ray luminosity that is more than an order of magnitude below the typical z > 1.5 galaxies with X-rays detected in deep fields (Fig. 2).

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### Table 1 | Properties of the X-ray arc

| Observed X-ray luminosity (erg s⁻¹) | L₁,-₀.₅  | 8.3 ± 1.7 × 10^{42} |
|------------------------------------|----------|---------------------|
| l₁₂₀₀  | 6.2 ± 1.3 × 10^{41} |
| L₁₂₀₀  | 4.7 ± 1.7 × 10^{40} |
| log(Mₙ/M*ₘ) <8.0 |
| Ê(B−V)ₚₖₖ <0.15 |
| SFR₀ₙₙ (₁₂₀₀ yr⁻¹) = 0.8 ± 0.4 |
| SFR₁ₐₐ (₁₂₀₀ yr⁻¹) = 0.5 ± 0.3 |
| Electron density, nₑ (cm⁻³) = 1,000 ± 200 |

Uncertainties reported are 1σ (68% confidence interval). *Reported SFRs include measurement and extinction uncertainties.
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from their stellar populations than more typical ‘main sequence’ star-forming galaxies, and that factors beyond SFR and metallicity—such as stellar population age \(17\) and sSFR \(14\)—are important for explaining the X-ray emission associated with star-forming galaxies.

This elevated X-ray luminosity reflects a phase in the life cycle of star-forming galaxies during which HMXBs are present in large numbers. High-mass stellar binaries are thought to be important, if short-lived, contributors to high-energy emission in all galaxies that are dominated by young stellar populations, a stage through which all galaxies pass at some point in their evolutionary history. The X-ray-emitting giant arc in SPT-CLJ2344-4243 is a potential analogue of the first generation of galaxies that contributed to reionizing the Universe. Specifically, X-ray emission from young galaxies is likely an important contributor to the ionizing radiation budget, driven by emission from HMXB systems in nascent star-forming galaxies\(18\)–\(30\). Young stellar populations (age \(\lesssim 30\) Myr) may also play a key role in clearing out the interstellar medium, allowing ionizing radiation to escape galaxies, by generating powerful winds from HMXBs that can inject substantial mechanical power into their local environment\(31\). Understanding the relationship between low-mass young star-forming galaxies and their HMXB populations is, therefore, crucial for understanding the physics of star formation across cosmic time and the reionization of the Universe by the first generation of stars and galaxies. In this lensed galaxy we are observing a typical low-mass, star-forming galaxy during the first third of the lifetime of the Universe, demonstrating how X-ray observations assisted by magnification from gravitational lensing enables studies that address the physical relationship between star formation and HMXB populations.

Our detection of a strongly lensed giant arc in the X-ray is an important first step that opens a new observational window into the formation of massive stars and HMXBs. This work demonstrates that X-ray facilities can be used in concert with strong lensing to push the limits of current X-ray telescopes and significantly improve our understanding of high-energy astrophysical phenomena. The combination of a deep Chandra exposure and high amplification by the foreground lensing potential produces an X-ray image of this distant galaxy at a depth equivalent to \(~1\) year (40 megasecond (Ms)) Chandra exposure. It is also important to note that this detection was discovered serendipitously, and that while the X-ray arc in SPT-CLJ2344-4243 is highly magnified, it is also intrinsically very faint. Targeted observations of the brightest, highest magnified giant arcs would enable much higher signal-to-noise X-ray detections with Chandra, with the potential
to construct samples of X-ray-detected star-forming galaxies at high redshift in the near term. Furthermore, the next generation of X-ray observatories currently in development will be orders of magnitude more sensitive than Chandra. This discovery previews the kind of measurement that future missions will be capable of making en masse. An unlensed analogue of this lensed galaxy would require a ~2 month (4 Ms) integration—equivalent to a deep field—with the NASA Probe-class mission concept design for the Advanced X-ray Imaging Satellite (AXIS), and a ~5 day (~0.4 Ms) exposure with the proposed Chandra successor mission concept, Lynx. The combination of strong lensing with the sensitivity of proposed future X-ray missions would enable detailed studies of the brightest, most highly magnified star-forming galaxies, as well as ultra-deep searches for X-ray emission from galaxies out to z ~ 10. The former will spatially resolve X-ray emission from individual, distinct star-forming regions—and thereby link HMXB populations with the fundamental physical scales (that is, sub-galactic) on which stars formed in the distant Universe—while the latter will provide a powerful tool for studying the reionization history of the Universe.

Methods

**Chandra X-ray Observatory data.** X-ray data for SPT-CLJ1234-4234 was obtained with Chandra ACIS-I over a series of programs in Cycle 12 (PI: Garmire, OBSID: 13401), Cycle 15 (PI: McDonald, OBSID: 16135, 16345), and Cycle 18 (PI: McDonald, OBSID: 19581, 19582, 19583, 20630, 20631, 20634, 20635, 20636, 20797). In total, this galaxy cluster was observed for a total of 551 ks, yielding roughly 300,000 counts in the 0.5–7.0 keV band. All Chandra data were first reprocessed using CIAO v4.10 and CALDB v4.8.0. Flares were identified following the procedure outlined by the calibration team and described online at http://cxc.harvard.edu/ciao/threads/flare/, using the 2.3–7.3 keV bandpass, time steps of 519.6 s, and a minimum length of 3 time bins. A merged, exposure-corrected image was generated using the CIAO ‘merge_obe’ script, covering the broad energy range 0.5–7.0 keV. The bandpass was chosen to span the full sensitivity range of ACIS-I, while avoiding the high particle backgrounds at E > 7.0 keV. Point sources were identified on separate merged images in the 0.7–2.0 and 2.0–7.0 keV bands, using the WVDECOMP tool in the ZHTOOLS package. The resulting list of point sources was used to generate a mask, which was applied to the broadband image.

The foreground emission from a faint, unresolved background target can produce shapes that closely mimic those of a strongly lensed object. We observed the giant arc, as well as several other lensed, multiply-imaged background sources, with the Folded-port InfraRed Echellelette (FIRE) spectrograph at the Magellan-I Baade telescope on 27–28 August and 20–21 September 2018. FIRE delivers spectra with a resolution of 0.82–2.5 μm and a throughput of 63 km s⁻¹ μm⁻¹. The resolving power of FIRE is ~400 in size. This size constraint is computed from the Chandra PSF and the strong-lensing magnification (strong-lens modelling is described in detail in the section ‘Gravitational lens modelling’ below), and is consistent with typical star-forming regions, such that the X-ray emission could easily result from a population of HMXBs in regions of the lensed galaxy that are unresolved by FIRE. We measured the precise flux from the giant arc using the ICM-free beta-model subtracted image. The flux from each image is strongly peaked in a central pixel, consistent with the Chandra PSF, and so we treated the two X-ray images as deprojected (point) sources. The background was computed from circular apertures and an algorithm based on the open-source IRAF/PyRAF aperture photometry APHOT package. We measured total X-ray counts from the giant arc using two apertures with radii of 0.5″ and 1.0″, representing the 77% and 92% enclosed energy radii, respectively. In the 0.5″ and 1.0″ apertures we measured statistically identical fluxes, and so we used the higher signal-to-noise measurement to estimate the luminosity. We measured statistically identical fluxes in the 0.5–7.0 keV band. All Chandra data were reprocessed using CIAO v4.10 and CALDB v4.8.0. Flares were identified following the procedure outlined by the calibration team and described online at http://cxc.harvard.edu/ciao/threads/flare/, using the 2.3–7.3 keV bandpass, time steps of 519.6 s, and a minimum length of 3 time bins. A merged, exposure-corrected image was generated using the CIAO ‘merge_obe’ script, covering the broad energy range 0.5–7.0 keV. The bandpass was chosen to span the full sensitivity range of ACIS-I, while avoiding the high particle backgrounds at E > 7.0 keV. Point sources were identified on separate merged images in the 0.7–2.0 and 2.0–7.0 keV bands, using the WVDECOMP tool in the ZHTOOLS package. The resulting list of point sources was used to generate a mask, which was applied to the broadband image.

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multiply-imaged background sources to constrain a strong-lensing model of the foreground galaxy cluster.

In the raw 2D science frames, we identified emission lines for a total of 11 sources, including the giant arc. None of the science targets exhibited smooth continuum emission. For emission line sources, the FIRE reduction pipeline (FIREHOSE) takes user-supplied positions of visually identified emission lines to fit a model for the source trace. Given emission line positions and a trace model, FIREHOSE extracts object spectra by jointly fitting the source trace along with the 2D sky spectrum using the regions along the slit that are not illuminated by the source. The extracted source spectra were flux calibrated using spectra of A0V stars taken at similar airmass, and coincident to within 1h, of each science frame. Telluric absorption was corrected using the stelloc procedure as a part of the spectropipeline, which is called as a part of the FIREHOSE reduction process.

We measured cosmological redshifts for each source with an extracted FIRE spectrum by identifying the velocities of nebular elements of 

$[\text{O} \text{II}]$ at 3729 Å and 0.75 μm, and set by the 0.75 μm data we have placed a 1σ upper limit on the amount of dust extinction at E(B–V) = 0.36. All of these measurements are uncorrected for the lensing magnification, and uncertainties are 1σ.

We find that the lens plane is adequately modelled by this procedure, with the best-fit resulting in an image–plane root-mean–square scatter of 0.37 arcsec. All the sets of multiple images are reproduced by the model. The multiply-imaged lensed galaxies, their positions and redshifts are given in Supplementary Table 2. The reconstruction of the galaxy in the source plane was done by ray-tracing the pixels of the images from the image plane to the source plane, by computing their source-plane position using the lensing equation and the deflection field of the best-fit model. The apparent difference between the two image reconstructions is due to the so-called lensing PSF, caused as the lensing potential distorts the background source. This was accounted for by forward-modelling the source images, which is beyond the scope of this paper.

Hubble Space Telescope imaging. We used Hubble imaging in three optical bands, F475W, F775W and F850LP, which are shown in Supplementary Fig. 1. The Channel 1 and 2 data consist of six dithered exposures with a 0.6″ × 0.6″ integration in each band. The Channel 1 data are deeper, with a 1σ upper limit on the apparent (not corrected for magnification) NIR luminosity (1.5 μm in the rest frame) of L(1.5 μm) < 1.7 × 10$^9$ L$_\odot$.

Gravitational lens modelling. We computed a strong-lensing model for the foreground galaxy cluster, SPT-CLJ2344-4243, using the public software Lenstool14. Lenstool uses a parametric approach, with Markov chain Monte Carlo sampling of the parameter space to identify the best-fit set of parameters and estimate statistical uncertainties. The foreground lens redshift of z = 0.595 is estimated from spectroscopy of four cluster members. We fit the observed 2D sky spectrum using the regions along the slit that are not illuminated by the source. The extracted source spectra were flux calibrated using spectra of A0V stars taken at similar airmass, and coincident to within 1h, of each science frame. The observed source spectra were then fit as a function of the lensed galaxy to be approximately 1,000 km s$^{-1}$.

Photometry of the lensed galaxy was measured in each band of Hubble imaging by a pseudo-isothermal ellipsoidal mass distribution with seven free parameters: position x, y, ellipticity η, position angle, core and cut radii, and a normalization σ. As is common practice in computing strong-lensing models for clusters of galaxies, the lens is modelled as a cluster-sized halo, supplemented by less-massive foreground member galaxies. In the strong-lensing regime, all the parameters are allowed to vary with the exception of the cut radius that cannot be constrained by the strong-lensing observables alone. The position, ellipticity and position angle of galaxy–scale halos are fixed to their observed properties as measured from the Hubble Space Telescope imaging data using Source Extractor10.

The core and cut radii and the normalization are scaled to the optical luminosity of each galaxy as measured with Source Extractor. Cluster-member galaxies are selected based on their colour in a colour-magnitude diagram using the red-sequence technique.

We identified several sets of multiply-imaged galaxies, whose positions and redshifts are used to constrain the lens model. Preliminary lens models were used in order to identify additional constraints, and lensed galaxies were subsequently spectroscopically confirmed and their redshifts measured with the Spitzer Space Telescope imaging data using Source Extractor10. The core and cut radii and the normalization are scaled to the optical luminosity of each galaxy as measured with Source Extractor. Cluster-member galaxies are selected based on their colour in a colour-magnitude diagram using the red-sequence technique.

Spitzer Space Telescope imaging. SPT-CLJ2344-4243 was observed with Spitzer/Infrared Array Camera (IRAC) during Cycle 8 as a part of program no. 80012 (principal investigator: M.B.). The observations consisted of 8 × 100 s and 6 × 30 s dithered exposures in IRAC Channels 1 (3.6 μm) and 2 (4.5 μm). These data probe rest-frame wavelengths of 1–2 μm, providing useful constraints on the total stellar mass (including older stars) in the lensed galaxy. The Channel 1 data are the deeper of the two, with a 10σ point source depth of 20.3 magnitudes and a final effective PSF of 1.66″. We used a reduction of the data produced for previous published work10, with the same pipeline and procedure as previously described. Spitzer/IRAC photometry was measured using the same apertures that were defined from the Hubble data described in the previous section, convolved with the larger Spitzer/IRAC PSF. The region of sky around the giant arc is relatively isolated in the IRAC imaging, even with the larger PSF. Forced photometry in apertures matched to the Hubble data yields statistical non-detections in both IRAC bands, with 3σ upper limits of 5 ± 13 μJy in IRAC Channel 1 (3.6 μm) and 1 ± 23 μJy in IRAC Channel 2 (4.5 μm). From the deeper 3.6 μm data we have placed a 1σ upper limit on the apparent (not corrected for magnification) NIR luminosity (1.5 μm in the rest frame) of L(1.5 μm) < 1.7 × 10$^9$ L$_\odot$.
Multiple line ratios constrain the relative metal enrichment—measured as the ratio of oxygen to hydrogen atoms in nebular gas. The giant arc is faint, and the large uncertainties on individual line flux measurements in the giant arc limit the precision on any metallicity constraints that we can place. We therefore perform the exercise of computing the metallicity, \(12 + \log(O/H)\), using several "strong line" diagnostics. The N2 diagnostic uses the ratio of \([N\,II]/\text{H}\alpha\) emission as a proxy for the metallicity, using a locally calibrated scaling relation. This diagnostic estimates 12 + \log(O/H) = 8.1 ± 0.4 for the lensed galaxy. The O3N2 diagnostic uses four different lines, as it takes as an input the ratio of two line ratios, \([O\,III]/[N\,II]\) and \([O\,III]/\text{H}\beta\) divided by \([N\,II]/\text{H}\alpha\); this diagnostic estimates 12 + \log(O/H) = 8.1 ± 0.2. These different diagnostics consistently indicate that the X-ray-emitting arc has a metallicity that is in the range \(0.15–0.4\,Z_\odot\) using recent measurements of the solar 12 + \log(O/H) metallicity\(^1\).

### Star-formation rate and stellar mass estimates

We estimated the SFR of the lensed X-ray arc from both the measured \(H\alpha\) emission line and the rest-frame UV stellar continuum emission. The SFR was estimated by computing the observed \(H\alpha\) luminosity of the giant arc and then following the standard prescription\(^2\) for Case B recombination, and including an aperture correction for the fraction of the giant arc that fell within the \(H\alpha\) slit. The resulting apparent \(H\alpha\) SFR is 20 ± 4 M\(_\odot\), yr\(^{-1}\). We then computed the true, intrinsic SFR by correcting for the average magnification affecting the portion of the arc that fell within the FIRE slit—a factor of 65 ± 20—resulting in \(SFR_\text{true} = 0.4 ± 0.1\,M\_\odot\,\text{yr}^{-1}\), where the reported uncertainty is the 1σ confidence interval. This measurement represents a minimum SFR, assuming the stars are associated with obscured star formation. We used the upper limit on the extinction from the hydrogen Balmer line ratio to compute an upper limit on the SFR of 1.2 M\(_\odot\), yr\(^{-1}\).

We computed a second SFR estimate based on the observed UV stellar continuum emission\(^3\), using the Hubble F475W imaging, which samples a rest-frame wavelength of 1.900 Å for the giant arc. The \(H\alpha\) redshift and magnification of the giant arc were first computed at the giant arc at rest-frame 1.900 Å to be \(M_{12} = 16.3 ± 0.4\). The scaling between UV luminosity and the SFR is sensitive to the properties of the underlying stellar population, such that the inferred SFR from a single UV luminosity changes by 42% for a 100 Myr versus 10 Myr old stellar population\(^4\). If the X-ray emission that we observe is associated with HMBXs, as we argue below, then the observed emission from the giant arc in SPT-CLJ2344-4243 is likely to be dominated by a young (<30 Myr) population. We can infer that the stellar population of the X-ray-emitting arc is young, but we lack a precise measurement of its age. Therefore, we use the SFR scaling estimator calibrated for a very young (10 Myr) population, but we note that the \(L_{UV}\) to SFR scaling factor varies systematically with stellar population age, increasing as age decreases. To reflect this fact, we include an additional 40% systematic uncertainty in the stellar population age that reflects the range of \(L_{UV}\) to SFR conversions between 10 and 100 Myr old stellar populations. Assuming a young stellar population age result in an apparent UV continuum SFR estimate of 19 ± 8 M\(_\odot\), yr\(^{-1}\), uncorrected for the lensing magnification. Applying a magnification correction using the light-weighted average magnification—a factor of 60 ± 20— for the photometric aperture that we used to measure the F475W flux, we recover an intrinsic SFR\(_\text{true} = 0.2 ± 0.1\,M\_\odot\,\text{yr}^{-1}\). If we apply the upper limit on the rest-frame extinction from above, then the resulting constraint is SFR\(_\text{true} < 1.0\,M\_\odot\,\text{yr}^{-1}\). Ideally, we would also incorporate a rest-frame infrared (IR) measurement of the SFR to directly constrain the unknown obscured star formation. Because we have no data on the giant arc at wavelengths longer than 4.5 μm (1.8 μm in the rest frame), we must rely solely on extinction-corrected optical and UV estimates of the total SFR. We are encouraged that the SFRs derived from the UV continuum and \(H\alpha\) emission line flux are in excellent agreement, despite being subject to very different extinction correction factors.

Throughout this paper we use SFR estimators for both \(H\alpha\) and UV-based SFR estimates would be 68% and 63% of the total SFR. We are encouraged that the SFRs derived from the UV continuum emission are in excellent agreement, despite being subject to very large uncertainties (0.00012 in redshift, 30 km s\(^{-1}\) in velocity). The Chandra PSF is sufficiently small to localize the X-ray emission to one of the two UV-bright clumps in the lensed galaxy, specifically, the northernmost west (upper right clump in the source-plane images; Supplementary Fig. 5) of the two UV-bright clumps. If the X-ray emitting region were located elsewhere above the 3σ detection, then the X-ray emission implies that the emitting source(s) are confined to a region with diameter ≤ 400 pc. This size is comparable to large star-forming regions, so that the unresolved X-ray detection of this lensed galaxy is consistent with what a population of HMBXs formed in a large star-forming region (or complex of smaller star-forming regions) within the lensed galaxy.

Finally, we also consider the possibility that the X-ray emission results from a chance projection of a background X-ray source onto the location of the optical giant arc. The primary evidence against this possibility is the precise alignment between the two X-ray sources and the two strongly lensed optical images of the galaxy. The strong-lensing configuration here is that of a merging image pair, and in the case of the strong-lensing map flip between the physical and X-ray images of the lensed galaxy exhibit this parity flip exactly as predicted for strong lensing, while the scenario in which these images are random projections is exceedingly unlikely, as it would require the random coincidence in location of two X-ray sources with the two ends of the optical giant arc. The surface density of X-ray sources in deep fields is approximately 1 every 1,000 square arcseconds\(^5\), so we can examine it in the context of other samples spanning several decades in stellar mass. In that context, an order of magnitude stellar mass limit is sufficient to the task.

### The origin of the observed X-ray emission

We have used multi-wavelength follow-up data to determine whether the observed X-ray emission is associated with star formation or AGN activity. The best constraints come from the ratios of strong rest-frame optical emission lines that we plot on the classic Baldwin, Phillips and Terlevich (BPT) diagram. As discussed above, the unobscured AGN-like diagnostic at high redshift are rare, but we note that the dominant sources of ionizing radiation in galaxies\(^6\) are AGN. In the BPT diagram we see that the X-ray-emitting lensed galaxy in SPT-CLJ2344-4243 lies in the region occupied by \(z\sim 0\) star-forming galaxies in the Sloan Digital Sky Survey (SDSS)\(^7\), as well as dwarf starburst galaxies in the local Universe that have measured X-ray luminosity\(^8\)-to-SFR scaling relations. In the BPT diagram we see that the X-ray-lensed galaxy is consistent with what we would expect for a low-luminosity AGNs in the local Universe with X-ray luminosities similar to our lensed galaxy still sit squarely within the AGN region of the BPT diagram. We also note that the rest-frame optical lines used to place the X-ray arc in the BPT diagram resulted from observations in which the vast majority (~90%) of the integration time had the FIRE slit positioned so as to fall directly on top of the X-ray-emitting giant arc. Therefore, we have been sensitive to AGN-like X-ray-emitting giant arcs. We do not have any data constraining the properties of the lensed galaxy at wavelengths longer than ~2 μm, and so we cannot test for the presence of an IR excess, but such a signature would also be quite surprising given the low dust content and stellar mass of the lensed galaxy.

Examining the available X-ray data, we compared the observed hardness ratio of the lensed source to samples of distant galaxies and AGN with X-ray detections. The limited available counts results in a large uncertainty in the hardness, 0.2 ± 0.3, which, but this value is broadly consistent with measured hardness ratios of the z ≥ 1 star-forming galaxies detected in X-ray deep fields, which tend to have positive hardness ratios\(^9\). Distinct AGN can have a broad range of hardness ratios, depending on the column density of absorbing neutral hydrogen (N\(_H\)), but less obscured AGN (N\(_H\) ≤ 10\(^20\) cm\(^{-2}\)) tend to have negative hardness ratios\(^10\). We also look to the source-plane reconstruction of all of the observed emission from the lensed galaxy for evidence of its origin. Supplementary Fig. 5 reveals that the giant arc is intrinsically a small (τ ≤ 1 kpc) blue galaxy with UV emission coming from two spatially resolved star-forming regions separated by ~500 pc in projection. The FIRE spectroscopy includes slits that targeted each of the two star-forming clumps, confirming that they share a common redshift, being identical to within the measurement uncertainties (0.00012 in redshift, 30 km s\(^{-1}\) in velocity). The Chandra PSF is sufficiently small to localize the X-ray emission to one of the two UV-bright clumps in the lensed galaxy, specifically, the northernmost west (upper right clump in the source-plane images; Supplementary Fig. 5) of the two UV-bright clumps. If the X-ray emitting region were located elsewhere above the 3σ detection, then the X-ray emission implies that the emitting source(s) are confined to a region with diameter ≤ 400 pc. This size is comparable to large star-forming regions, so that the unresolved X-ray detection of this lensed galaxy is consistent with what a population of HMBXs formed in a large star-forming region (or complex of smaller star-forming regions) within the lensed galaxy.
and so the odds of such two sources randomly falling on two specific locations in the sky, localized to the precision of our data (~0.3°), is approximately 1 in 10^6. The odds of this happening become vanishingly small when we also consider that the two X-ray images have the same observed X-ray flux (to within the uncertainties), as would be expected for two similarly magnified images of the same galaxy.

Given all of the available evidence, we have concluded that the X-ray emission detected from the giant arc in SPT-CLJ2344-4243 is generated predominantly by stellar-mass compact object systems associated with recent star formation. The available data cannot absolutely rule out the presence of a very faint/obscured AGN, but we argue that this interpretation for the observed X-ray emission is much less likely than HMXBs. We come to this conclusion based on the weight of the evidence, including the BPT lines, the nature and morphology of the galaxy (consistent with a low-mass dwarf starburst), and the X-ray emission being clearly associated with a UV-bright star-forming region that is spatially resolved in the Hubble imaging.

Observations of local dwarf starburst galaxies have demonstrated that it is common for these objects to have X-ray emission resulting from HMXBs and ultra-luminous X-ray sources associated with young stellar populations. This picture is further supported by our nearest example of a starburst galaxy, M82, in which the individual HMXB sources have been spatially resolved and well studied. There have been two cases reporting potential low-luminosity X-ray AGN in dwarf starburst galaxies that fall into the star-forming region of the BPT diagram as the giant arc analysed here. However, a deeper follow-up X-ray study of one of these galaxies revealed that the dominant source of X-ray emission is likely to be the HMXBs associated with star-forming regions, with no AGN that is present being sub-Eddington and much fainter (L_x < 10^{38} erg s^{-1}). We conclude that the weight of the evidence overwhelmingly points toward star formation as the source of the observed X-ray emission in the giant arc.

Data availability

The data that support the plots within this paper and other findings of this study are available from the corresponding author upon reasonable request. This paper makes use of Chandra data from observation IDs 13401, 16135, 16545, 19581, 19582, 19583, 20630, 20631, 20634, 20635, 20636 and 20797. All raw Chandra data are available for download at the Harvard Dataverse (https://doi.org/10.7910/DVN/JCFRLB).

Code availability

The data reduction pipelines used in this work are all publicly available. Chandra data were reduced using the CIAO package (http://cxc.harvard.edu/ciao/), Hubble data were reduced using Drizzlepac (http://drizzlepac.stsci.edu/), and FIRE data were reduced using the FIREHOSE package (http://web.mit.edu/rscwmo/www/FIRE/ob_data.htm). The modelling of the foreground galaxy cluster potential was done using the publicly available LensTool code (https://projet.lam.fr/projects/lenstool/wiki). Analysis of the FIRE spectra was performed using the IDL Astronomy User's Library (https://idlastro.gsfc.nasa.gov/).

Received: 30 April 2019; Accepted: 9 August 2019;

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Acknowledgements
Support for this work was provided by NASA through Chandra award number GO7-18124, issued by the Chandra X-ray Observatory Center, which is operated by the Smithsonian Astrophysical Observatory for and on behalf of the National Aeronautics Space Administration under contract NAS8-03060. Additional support was provided by NASA through the Space Telescope Science Institute (HST-GO-15315), which is operated by the Association of Universities for Research in Astronomy, Incorporated, under NASA contract NASS-26555.

Author contributions
M.B.B. performed the analysis of the FIRE spectroscopy, Chandra, Hubble and Spitzer data, and wrote the article text with input and contributions from all authors. M.M. acquired the Chandra and Hubble data. M.B.B. and M.M. reduced the Chandra X-ray data. M.B.B. reduced the FIRE NIR spectroscopy, which was obtained from observations performed by M.B.B. and M.D.G. M.B. acquired the Spitzer data. M.F. reduced the Hubble data. K.S. computed the strong lensing model of the foreground cluster lens and produced the reconstruction of the galaxy in the source plane. The authors are ordered in two alphabetical tiers after M.F.

Competing interests
The authors declare no competing interests.

Additional information
Supplementary information is available for this paper at https://doi.org/10.1038/s41550-019-0888-7.

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Peer review information Nature Astronomy thanks Jean-Paul Kneib and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.

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NATURE ASTRONOMY | www.nature.com/natureastronomy
An X-ray Detection of Star Formation In a Highly Magnified Giant Arc

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Supplementary Information for “An X-ray Detection of Star Formation In a Highly Magnified Giant Arc”: 
| Ion  | Rest-frame Wavelength (Å) | $f_\lambda \times 10^{-18}$ erg cm$^{-2}$ s$^{-1}$ | 1 $\sigma$ error on $f_\lambda \times 10^{-18}$ erg cm$^{-2}$ s$^{-1}$ |
|------|--------------------------|---------------------------------------------|---------------------------------------------|
| [O II] | 3727.10                  | 6.1                                         | 1.6                                         |
| [O II] | 3729.86                  | 6.3                                         | 1.7                                         |
| Hβ   | 4862.70                  | 5.1                                         | 1.0                                         |
| [O III] | 4960.29                  | 6.5                                         | 1.1                                         |
| [O III] | 5008.24                  | 13.9                                        | 1.8                                         |
| Hα   | 6564.63                  | 11.1                                        | 1.5                                         |
| [N II] | 6585.42                  | 0.4                                         | 0.3                                         |
Supplementary Table 2 | List of Lensing Constraints

| ID | R.A. J2000 | Decl. J2000 | z_{spec} | z_{spec} Source | Notes |
|----|------------|-------------|---------|----------------|-------|
| 1.1 | 356.181065 | -42.719537 | 1.1485 | FIRE | Radial arc |
| 1.2 | 356.180015 | -42.719137 | 1.1485 | FIRE | Radial arc |
| 1.3 | 356.194399 | -42.721999 | — | — | — |
| 2.1 | 356.193637 | -42.718398 | 1.5244 | FIRE | X-ray source |
| 2.2 | 356.192454 | -42.716205 | — | FIRE | — |
| 2.3 | 356.179454 | -42.713201 | — | — | Predicted counter image |
| 2.4 | 356.175115 | -42.729047 | — | — | Predicted counter image |
| 3.1 | 356.182510 | -42.716901 | 1.5130 | FIRE | Radial arc |
| 3.2 | 356.182793 | -42.718304 | — | — | Radial arc |
| 3.3 | 356.178356 | -42.732671 | — | — | — |
| 4.1 | 356.18161 | -42.718569 | 3.1854 | FIRE | — |
| 4.2 | 356.187273 | -42.718805 | — | — | — |
| 5.1 | 356.165815 | -42.719573 | 1.9760 | FIRE | — |
| 5.2 | 356.165753 | -42.719721 | — | — | — |
| 5.3 | 356.165866 | -42.720521 | — | — | — |
| 5.4 | 356.190844 | -42.724246 | — | — | — |
| 5a.3 | 356.165860 | -42.720559 | — | — | — |
| 5a.4 | 356.190861 | -42.724208 | — | — | — |
| 5b.3 | 356.165787 | -42.720653 | — | — | — |
| 5b.4 | 356.190914 | -42.724083 | — | — | — |
| 6.1 | 356.164709 | -42.720192 | — | — | — |
| 6.2 | 356.164672 | -42.720768 | — | — | — |
| 8.1 | 356.189149 | -42.719243 | 1.4278 | FIRE | — |
| 8.2 | 356.169401 | -42.726908 | — | — | — |
| 8.3 | 356.184586 | -42.719816 | — | — | — |
| 8a.1 | 356.189016 | -42.719262 | — | — | — |
| 8a.2 | 356.169315 | -42.726879 | — | — | — |
| 9.1 | 356.181472 | -42.714693 | 1.5080 | FIRE | — |
| 9.3 | 356.177247 | -42.731010 | — | — | — |
| 10.1 | 356.194985 | -42.720406 | 2.9181 | FIRE | — |
| 10.2 | 356.165524 | -42.728406 | — | — | — |
| 10a.1 | 356.165609 | -42.728576 | — | — | — |
| 10a.2 | 356.194923 | -42.720238 | — | — | — |
| A | 356.169416 | -42.720220 | 1.2159 | FIRE | Single image |
| B | 356.169143 | -42.722700 | 1.2150 | FIRE | Single image |
| C | 356.191627 | -42.715342 | — | — | — |
| D | 356.194568 | -42.712562 | — | FIRE | Observed, no spec-z |
| E | 356.169583 | -42.716381 | — | — | — |
| F | 356.187354 | -42.727401 | 0.6500 | Bayliss+2016 | — |
| G | 356.171620 | -42.725820 | 0.2237 | Bayliss+2016 | — |
| Cluster | 356.18314 | -42.720148 | 0.596 | Bayliss+2016 | — |

The Right Ascension (R.A.) and Declination (Decl.) for all galaxies used as inputs for the strong lensing model described in Methods Section 5. All lensed background redshifts were obtained with the FIRE spectrograph on Magellan as described in the Methods Section 2. Cluster and foreground galaxy redshifts are taken from the literature\(^1\).
Supplementary Figure 1 | X-ray Surface Brightness Profile. The surface brightness profile of the foreground lensing galaxy cluster, SPT-CLJ2344-4243, is well measured out to a radius of more than 60 arcseconds, and in the region where the giant arc is located the cluster emission is spatially smooth, with 2.6 counts per *Chandra* pixel. The reduced 0.5-7 keV *Chandra* image used to measure the cluster surface brightness profile is inset in the upper right. The emission from the giant arc is visible even in the raw frame (indicated by the cyan hash marks).
Supplementary Figure 2 | Giant Arc X-ray Emission. Three panels show the region of sky containing the X-ray emitting giant arc in the rest-frame UV continuum (panel A; Hubble F775W), the raw X-ray (panel B; 0.5-7 keV channel), and the foreground cluster-subtracted X-ray (panel C; 0.5-7 keV channel). There is X-ray emission spatially coincident with each of the ends of the giant arc, both before and after subtracting off the diffuse foreground galaxy cluster emission (locations indicated by cyan hash marks). All panels have color bars below them that indicate the mappings between pixel colors and flux values; flux values are in units of 5e-16 erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$ panel A, and in 0.5-7 keV Chandra counts in panels B and C.
Supplementary Figure 3 | FIRE slit positions and Emission Line Spectra. In panel A we show the false color Hubble image with and inset zoom region on the X-ray emitting giant arc. The optical colors here represent Hubble imaging data in the F850LP (red), F775W (green), and F475W (blue) filters. In the inset we show the FIRE slit placement on the giant arc, with the positions of the multiply-imaged X-ray emission also indicated by the magenta contours; the contours are the 1/2/3/4σ levels for the individual detections of the X-ray images in a super-sampled version of the Chandra data. We label the two lensed images as 2.1 and 2.2, consistent with the naming scheme used below in Extended Data Figure 4. Spectra from all slit positions returned the same emission line pattern. The bottom panels show the rest-frame optical emission line spectrum of the giant arc that results from coadding the spectra obtained through all of the slit positions indicated in panel A; panel B shows the [O II] 3727,3729 doublet, panel C shows H–β and the [O III] 4960,5008 doublet, and panel D shows H–α and [N II] 6585.
Supplementary Figure 4 | Visualization of the Strong Lens Model. The false color Hubble image of SPT-CLJ2344-4243 is shown here with lens model constraints indicated by numbered image families (e.g., 2.1, 2.2, 2.3 and 2.4 indicate the four lensed images of the X-ray emitting arc). Spectroscopically confirmed redshifts of lensed background sources used in the modeling are shown in the top right corner, and color-coded to match the image family markers in the image and in Supplementary Table 2. The critical curve at the redshift of the X-ray arc (z=1.5244) is also shown in red. The optical colors here are given by Hubble imaging data in the F850LP (red), F775W (green), and F475W (blue) filters.
Supplementary Figure 5 | Source Plane Reconstruction of the Giant Arc. Here we show source–plane reconstructions of the lensed images 1 and 2 from the highly magnified giant arc with the centroid of the X-ray emission in the source–plane is indicated by the red cross in panels A and B, as well as of a less magnified—and therefore less distorted—third image (panel C). In panels D and E we show source–plane reconstructions of images 1 & 2 with the contour levels (cyan) from the top panel inset of Extended Data Figure 3 ray-traced into the source plane. The contours are the 1/2/3/4σ levels for the individual detections of the X-ray images in a super-sampled version of the Chandra data. These contours effectively represent the shape and extent of the Chandra PSF in the source plane and they show that the X-ray emitting UV–bright region in the lensed galaxy is at best marginally resolved in X-rays, thus explaining the point source nature of the detected X-ray emission. The strong lensing caustic (the critical curve mapped into the source plane) is shown as the solid yellow line in each source plane reconstructed image.
Supplementary Figure 6 | Optical emission line ratio diagnostic diagram. Gas in galaxies is generally ionized by either hot stars or active galactic nuclei; the ionizing source can generally be distinguished using the [O III] to Hβ and [N II] to Hα line strength ratios. Black solid and dashed lines indicate the boundaries between gas ionized by star formation, AGN, or by both SF and AGN in the local universe, while the dotted line shows the predicted evolution in the boundary between between star formation and AGN-dominated ionizing radiation at the redshift of our X-ray arc. Blue, green and red clouds of points are local galaxies from the Sloan Digital Sky Survey (SDSS). Red are galaxies known to contain active galactic nuclei (AGN), blue are star-forming galaxies, and green are composite star-forming + AGN galaxies. We also use larger symbols to over-plot two other comparison samples that have X-ray luminosities similar to the giant arc in SPT-CLJ2344-4243. The first, indicated by red x marks, are local low X-ray luminosity AGN (LLAGN). The second, indicated by blue filled squares, are local Lyman break galaxy (LBG) analogs, which are low-mass, UV-bright star-forming galaxies. All sources from the literature are plotted without error bars to make the plot easier to read; the literature uncertainties in both line ratios are typically <10% (i.e., <0.1 dex). The giant arc in SPT-CLJ2344-4243 is also plotted (purple filled star).
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