The First X-ray Detection of Star Formation In a Highly Magnified Giant Arc


SPT-CLJ2344-4243 (Phoenix Cluster)

References: see Bayliss et al. 2019 in Nature Astronomy for the complete published list.

The Origin of the X-ray Emission - The Evidence Favors High Mass X-ray Binaries

The Lensed X-ray Giant Arc Compared to Local and Deep Field Samples of X-ray Detected Star Forming Galaxies

The X-ray Detection of a Highly Magnified Giant Arc

The massive galaxy cluster, SPT-CLJ2344-4243 (the "Phoenix Cluster"), acts as a gravitational lens, magnifying our view of a background star forming galaxy. Remarkably, a deep (~600 kilosecond) observation taken with the Chandra X-ray Observatory reveals the presence of X-ray emission from the giant arc (Figure 1). A lensing analysis using Hubble and Spitzer imaging, as well as follow-up spectroscopy, confirms that the giant arc is formed from a pair of highly magnified (~60x) merging images of a background star-forming galaxy (Figures 2-5). The combination of a deep Chandra exposure and high lensing amplification produces an X-ray view of the lensed galaxy at a depth equivalent to ~1.3 year (40 megaseconds) Chandra exposure (Figure 6). The lensed galaxy is a low-mass (M/M_☉ < 10^9), low-metallicity starburst with elevated X-ray emission (Figure 7), and is a likely analog to the first generation of galaxies. The high 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 by galaxies that are dominated by young stellar populations, a stage through which all galaxies pass at some point in their evolutionary history. The source detected here was discovered serendipitously in archival data, but it demonstrates the potential for lensing-assisted X-ray observations of the brightest strongly lensed sources in the sky. This result paves the way for future work that will exploit strong lensing magnification in combination with Chandra, and its successor missions, to deliver highly resolved X-ray measurements of star formation and stellar populations in the distant universe. These lensing-assisted studies will isolate the X-ray emission from distinct star-forming regions—thereby linking HMXBs and stellar populations with the fundamental physical scales (i.e., sub-galactic) on which stars formed in the distant universe. This lensing analysis using Hubble imaging data in the 850LP (red), 7740 (green), and 4710 (blue) filters. Two sets of contours indicate the location of the X-ray emission from the giant arc in both Inset panels. The lensing geometry of the giant arc is a pair of merging images, where the lower and upper halves of the arc are each a single image with mirror symmetry.

Figure 2: Source-plane reconstructions of images 1 & 2 of the lensed X-ray arc, with the X-ray detections indicated by the cyan contours. These contours indicate the shape and extent of the Chandra X-ray emission (blue open circles; Basu-Zych et al. 2013b); and z~0.2-0.3 extreme emission line galaxies (open blue circles; Basu-Zych et al. 2013a, Kaaret et al. 2017); stacked high-redshift Lyman break galaxy analogs as blue filled circles; Svoboda et al. 2019 (green filled circles with crosshairs); Svoboda et al. 2018), and BPT (Baldwin et al. 1981) diagrams with X-ray detected giant arc plotted as a purple star, solid and dashed lines separate galaxies ionized by star formation (AGN), and by both star formation and AGN; local Lyman break galaxies (LBG) analogs as red x's and local Lyman break galaxy (LBG) analogs as blue filled squares.

Figure 3: (Right: Hubble image zoomed in on the X-ray emitting giant arc indicating where slits were placed to measure its rest-frame optical emission line spectrum. The location of the X-ray emission is indicated by the magenta contours. (Top:) Spectra from all slit positions returned the same rest-frame optical emission line pattern, shown here in several panels. Panel A shows the [O II] 3727,3729 doublet, panel B shows H–β and the [O III] 4959,5007 doublet, and panel C shows Hα and [N II] 6583.

Figure 4: (Left:) Hα+[N II] and [O II] emission line pattern, shown here in several panels. Panel A shows the [O II] 3727,3729 doublet, panel B shows H–β and the [O III] 4959,5007 doublet, and panel C shows Hα and [N II] 6583.

Figure 5: BPT (Baldwin et al. 1981) diagnostic diagram with X-ray detected giant arc plotted as a purple star, solid and dashed lines separate galaxies ionized by star formation (AGN), and by both star formation and AGN; local Lyman break galaxies (LBG) analogs as red x's and local Lyman break galaxy (LBG) analogs as blue filled squares.

Figure 6: The observed X-ray luminosity vs redshift for 3x-ray detected non-AGN galaxies, including local LBG Analogs (blue open circles), Basu-Zych et al. 2013a, Kaaret et al. 2017; “Green Pea” extreme emission line galaxies (GPs, green filled circles with crosshairs; Svoboda et al. 2018); and low-redshift star-forming galaxies in the local universe and in the northern and southern Chandra Deep Fields (orange filled circles/squares and red filled squares; Colbert et al. 2004, Lehmer et al. 2016, Luo et al. 2015). The X-ray arc is plotted as an open star for the observed (apparent) luminosity and as a filled star for the true, (intrinsic), lensing-corrected luminosity. The lensing amplification has allowed us to detect X-ray emission from a dwarf star-forming galaxy (z = 1.524) with an intrinsic, lensing-corrected luminosity that corrects Chandra deep fields only probe to 0.5. Approximate depths for hypothetical deep fields from two proposed future X-ray observatories, AXIS, and Lynx, are also plotted as the dotted black line.