FOUR IRAC SOURCES WITH AN EXTREMELY RED H—[3.6] COLOR: PASSIVE OR DUSTY GALAXIES AT z > 4.5?

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ABSTRACT

We report the detection of four IRAC sources in the GOODS-South field with an extremely red color of H—[3.6] > 4.5. The four sources are not detected in the deep Hubble Space Telescope WFC3 H-band image with Hlimit = 28.3 mag. We find that only three types ofSED templates can produce such a red H—[3.6] color: a very dusty SED with the Calzetti extinction of AV = 16 mag at z = 0.8; a very dusty SED with the SMC extinction of AV = 8 mag at z = 2.0–2.2; and an 1 Gyr SSP with AV ∼ 0.8 at z = 5.7. We argue that these sources are unlikely dusty galaxies at z ≤ 2 based on absent strong MIPS 24 μm emission. The old stellar population model at z > 4.5 remains a possible solution for the 4 sources. At z > 4.5, these sources have stellar masses of log(M/L⊙) = 10.6–11.2. One source, ERS-1, is also a type-II X-ray QSO with L2–8 keV = 1.6 × 1044 erg s−1. One of the four sources is an X-ray QSO and another one is a HyperLIRG, suggesting a galaxy-merging scenario for the formation of these massive galaxies at high redshifts.

Key words: cosmology: observations – galaxies: evolution – galaxies: formation – galaxies: high-redshift – infrared: galaxies

1. INTRODUCTION

Extremely Red Objects (EROs) are of great interests to modern astrophysics. A simple red color criterion generally selects two types of galaxies: those at high redshifts and those with heavy dust extinction. With rapid progress in telescope apertures and detectors, this red color selection always leads to new types of galaxies or galaxies at record-high redshifts. After large format near-infrared array cameras became available for astronomical surveys, people started to detect galaxies with very red R — K colors (Elston et al. 1988, EROs, R — K > 5 or I — K > 4). EROs were so rare in the early days that they were thought to be abnormal objects at very high redshifts. There have been more and more EROs detected by larger aperture telescopes with more advanced IR array cameras. Most EROs with R — K > 5 are now identified as elliptical and dusty galaxies at 0.6 < z < 1.5 (Thompson et al. 1999; McCarthy et al. 2001; Cimatti et al. 2002). One extreme case, an ERO with I — K = 6.5, was spectroscopically identified as a dusty Ultra-Luminous InfraRed Galaxy (ULIRG) at z = 1.44 (Elbaz et al. 2002). This source is analogous to a local ULIRG, Arp220. Smail et al. (2002) suggested that most dusty EROs at high redshifts are LIRG/ULIRGs. Spitzer/IRAC permits very fast imaging of sky in mid-infrared bands with great depth. Wilson et al. (2004) found that 17% of their IRAC 3.6 μm selected sample are EROs at z ≥ 1.

Red color criteria are practically diversified and applied to almost all kinds of photometry in optical and IR bands. But the physics for this type of criteria are limited to the following: (1) the Lyman break at 912 Å; (2) the Balmer and the accumulated absorption line breaks at 3648 Å and 4000 Å; or (3) dust extinction. Red color caused by the Lyman/Balmer break can be used to estimate redshifts. In most deep broad band imaging surveys, one could not tell if a red color is due to the Lyman/Balmer break or dust extinction (Steidel et al. 2003). An additional color in longer wavelength bands is usually applied together with the red color criterion to select galaxies at high redshifts. For example, U — g and g — R colors were used to select galaxies at z = 3 where the Lyman break shifts between U and g bands, commonly known as U dropout for red U — g color (Steidel et al. 2003). The dropout technique was applied in much longer wavelength bands to select galaxies at z = 6 ~ 9. Franx et al. (2003) used the near-IR (NIR) color J — K > 2.3 to select Distant Red Galaxies (DRGs) with the strong Balmer/4000 Å break shifting in between the J and K at z ~ 2. The NIR spectroscopy for DRGs by Kriek et al. (2007) shows that about half of their sample are passive evolved galaxies at z ~ 2, and the rest are dusty galaxies in a much wider redshift range. Several groups identified 24 μm luminous and optically faint or invisible sources with R — [24] > 14.2 (f24/FR > 1000) as very dusty ULIRGs at z ~ 2. These sources are confirmed spectroscopically by Spitzer/IRS and ground-based optical spectroscopy (Houck et al. 2005; Yan et al. 2007; Dey et al. 2008; Huang et al. 2009).

In this paper we report detection of four galaxies with extremely red colors of H—[3.6] > 4.5 in the Great Observatories Origins Deep Survey (GOODS)-South field. Only one similar source, a submillimeter galaxy (SMG) called GOODS 850-5 (aka GN10) in the GOODS-North field, was ever found to have H—[3.6] > 4.5. This SMG was also detected by the Submillimeter Array (Wang et al. 2007) with a high angular resolution of ∼2′′, permitting identification of its counterparts in shorter wavelength bands. Wang et al. (2009) performed ultra-deep J and H band imaging for this source with the NIC3 camera on the Hubble Space Telescope (HST). A total of 16 orbits of HST observation, reaching a nanoJansky depth in the F160W band, yields no detection for this source. Based on this red H—[3.6] color, they argue that its redshift is at z ≈ 4–6.5. Later, detection of CO(4–3) from this source confirms its redshift at z = 4.05 (Daddi et al. 2009). This study provides the first look at...
properties of this new type of object. More sources of this kind will be detected in the Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey (CANDELS; Grogin et al. 2011).

2. DEEP IR IMAGING OF GOODS-SOUTH

GOODS is the deepest multi-wavelength survey with space telescopes including HST, Spitzer, and Chandra (Dickinson 2004). The depth of GOODS IRAC 3.6 μm imaging reaches the sub-microJansky level. The deep NIR imaging of the GOODS-South field was selected for the Early Released Science (O’Connell 2010, ERS) for the Wide Field Camera 3 (WFC3), a fourth-generation UVIS/IR imager on board HST. We construct an H-selected multi-wavelength catalog including YJH+IRAC photometry in the ERS covered region. The IR images have very different angular resolutions: 0′03 for the HST WFC3 YJH band images and ∼2″ for the Spitzer IRAC 3.6–8.0 μm images. A photometry program called TFIT is specifically designed to perform photometry on a lower resolution image with input information of object positions and light distributions measured in a high-resolution image (Laidler et al. 2007). The TFIT program convolves a point-spread function (PSF) kernel to the high angular resolution stamp image for each object to construct lower angular resolution image templates and fit them to the lower angular resolution image. In our case, we ran the TFIT to perform photometry on the IRAC 3.6 μm image for the H-band selected galaxies detected in the ERS F160W image. The TFIT also produces a residual image after subtracting all H-band detected galaxies in the 3.6 μm image. We visually inspected the residual image and found four IRAC sources detected at 3.6 μm with no H-band counterparts shown in Figure 1. The limiting magnitude for the input H-selected sample is $H = 28.3$ mag at 3σ level, therefore these sources are fainter than $H = 28.3$ mag and have colors redder than $H - [3.6] = 4.5$.

We searched for counterparts of these four sources in all available wavelength bands in the GOODS-South field. All four sources are detected in the remaining three IRAC bands. None of these sources are detected in the GOOD-South ACS BVIZ images with the 5σ limiting magnitudes of 28.65, 28.76, 28.17, and 27.93, respectively. The K band is the only band available in between H and 3.6 μm, permitting further constraint on its SED and photometric redshift. The 5σ limiting magnitude for the K-band image of the GOODS-South field (Retzlaff et al. 2010) is 24.4 mag and none of our sources is detected in K band. Far-IR (FIR) observation is also critical in determining properties of these red sources (Wang et al. 2009). ERS-3 is clearly detected at 24 μm and ERS-2 is marginally detected at ∼3σ level. We inspected the Herschel/Spire deep imaging of the CDFS and found that only ERS-3 is marginally detected at 250 μm and 350 μm. The PSF for the SPIRE 500 μm band image is too broad (36′′) to permit accurate extraction of flux density for ERS-3 (Huang et al. 2011). ERS-3 is also detected at 1.4 GHz with $f_{1.4\text{GHz}} = 29.2 \pm 8 \mu$Jy. The remaining three sources are not detected in radio with $f_{1.4\text{GHz}} < 24 \mu$Jy. No submillimeter/millimeter source is detected in the locations of these four sources (Scott et al. 2009; Weiβ et al. 2009). Another source, ERS-1, is an X-ray source in the Chandra 2 Ms catalog (Alexander et al. 2003). ERS-2 and ERS-4 are detected only in four IRAC bands (Table 1).

3. SEDs, PHOTOMETRIC REDSHIFTS, AND PROPERTIES OF THE EXTREMELY RED OBJECTS

For three out of the four sources in this study, only NIR+IRAC flux densities are available for their photometric redshift estimation. The most predominant feature in their SEDs is the extremely red color of $H - [3.6] > 4.5$. We first rule out that these sources are brown dwarfs. A brown dwarf with $T = 600$ K has $H - [4.5] > 4.0$ (Legget et al. 2010); such a brown dwarf should

![Figure 1. Stamp images for the four H-band dropout objects in the GOODS-South field in the F160W and 3.6 μm bands. ERS-3 is marginally detected at 24, 250, 350 μm, and 20 cm. ERS-1 is an X-ray source detected in the Chandra 2 Ms imaging (Alexander et al. 2003).](image)

**Table 1**

| Name  | R.A.  | Decl. | F160W | K   | 3.6 μm | 4.5 μm | 5.8 μm | 8.0 μm | 24 μm |
|-------|-------|-------|-------|-----|--------|--------|--------|--------|-------|
| ERS-1 | 53.084726 | −27.707964 | 0.0066 ± 0.002 | 0.2904 ± 0.1398 | 1.23 ± 0.03 | 1.97 ± 0.04 | 3.04 ± 0.24 | 3.25 ± 0.26 | −11.7 ± 3.8 |
| ERS-2 | 53.132749 | −27.720144 | 0.0036 ± 0.002 | −0.0431 ± 0.1681 | 1.54 ± 0.20 | 1.56 ± 0.10 | 2.03 ± 0.26 | 3.21 ± 0.28 | 14.7 ± 4.0 |
| ERS-3 | 53.060827 | −27.718263 | 0.0019 ± 0.002 | 0.0727 ± 0.1398 | 1.05 ± 0.03 | 1.41 ± 0.05 | 1.75 ± 0.23 | 2.24 ± 0.25 | 39.5 ± 4.3 |
| ERS-4 | 53.167161 | −27.715316 | 0.0054 ± 0.002 | 0.2628 ± 0.1382 | 0.57 ± 0.06 | 0.66 ± 0.06 | 1.25 ± 0.25 | 0.87 ± 0.28 | 5.9 ± 3.6 |

**Note.** All flux densities in this table are in unit of μJy.
have $3.6 - [4.5] > 1$ due to the methane absorption at 3.6 $\mu$m in its photosphere. All of our sources have $3.6 - [4.5] < 0.5$. It is unlikely that this red color is due to the Lyman break at $z > 15$. Galaxies with a strong Balmer/4000 Å break at $3 < z < 8$ can have very red $H - [3.6]$ colors. Recently Richard et al. (2011) detected a lensed source at $z = 6.02$ behind cluster A383 with $H - [3.6] = 1.5$, arguing that this is a possible passive galaxy. A few more lensed galaxies with extreme red optical–MIR color are identified to be dusty galaxies at either $z \sim 2$ or $z > 6$ (Boone et al. 2011; Larpote et al. 2011). Their $H - [3.6]$ colors are only in range of 0.5 < $H - [3.6] < 2$.

3.1. SED Fitting

We model the $H - [3.6]$ color using stellar population models of both BC03 (Bruzual & Charlot 2003, BC03) and the upgraded model CB07 (S. Charlot & G. Bruzual 2007, private communication) emphasizing on asymptotic giant branch star contribution in the rest-frame NIR bands. The templates are constructed with various stellar populations of the solar metallicity and a very wide range of dust extinction of $0 < A_V < 25$. The star formation history used in constricting the template set includes single burst, exponential decreasing with various e-fold times, and constant rates. Two types of extinction curves are used in the SED templates: the widely used Calzetti extinction curve for galaxies (Calzetti et al. 2000) and the SMC extinction curves (Gordon et al. 2003). Both extinction curves are only up to 2.2 $\mu$m, while our detected photometry points for the four sources are in 3.6 $\mu$m < $\lambda$ < 8.0 $\mu$m. We extend both curves to the IRAC bands using the mid-IR (MIR) dust extinction curve in 3.6 $\mu$m < $\lambda$ < 24 $\mu$m (Chapman et al. 2009).

We first fitted our model templates to GOODS 850-5 to investigate what kind of stellar population and how much dust extinction can make such a red $H - [3.6]$ color. GOODS 850-5 is already known at $z = 4.05$, and thus provides a better constraint on stellar population and dust extinction. Both BC03 and CB07 models with either Calzetti or SMC extinction yield a similar result for GOODS 850-5: a 1 Gyr old single stellar population with a modest extinction of $A_V = 2.4$–3.6. The best-fit template is a 1 Gyr single stellar population model with the Calzetti extinction of $A_V = 3.6$. Wang et al. (2009) obtained a similar model template for their best-fitting but yielded much higher redshifts at $z = 6.9$.

We argue that the four objects in this study are at the same redshifts: they have very similar SEDs, and their positions are very close to each other, with a mean distance of $\sim 1.5$ to their closest neighbors. We fitted the SED templates to the six IR photometry points (H, K, and four IRAC bands) for each object in the sample. Our fitting yields two extreme solutions with the Calzetti extinction: a very dusty template with $A_V = 16$–18 at $z \sim 0.8$ and an old stellar population template with $z \sim 5.7$ and $A_V \sim 0.8$ (Figure 2). The templates with the SMC extinction yield a similar dusty solution with $A_V = 7$–8 at $z \sim 2.2$. By applying heavy dusty extinction with $A_V > 7$ to templates, its shape and the resulting photometric redshift are only determined by extinction curves. For example, the SMC extinction curve yields a photometric redshift of $z_p = 2.2$ for our objects, which is caused by a dip at 1.25 $\mu$m in the SMC extinction curve ($A(1.65 \mu m)/A_V = 0.169, A(1.25 \mu m)/A_V = 0.131$, and $A(0.81 \mu m)/A_V = 0.567$; Gordon et al. 2003). With a very high $A_V$ value, this feature is amplified. At $z = 2.2$, this extinction dip shifts to the IRAC 3.6 $\mu$m band to make $H - [3.6]$ redder and $[3.6] - [8.0]$ bluer. The photometric redshifts obtained with the SMC extinction curve are mainly driven by this feature.

There are generally three final solutions (Figure 2) in our SED fitting for the four objects: a dusty template at $z = 0.8$ with the Calzetti extinction of $A_V = 16$, a dusty template at $z = 2.2$ with the SMC extinction of $A_V = 8$, and an old stellar population template with age of 1 Gyr and $A_V < 1$. Though each solution has a slightly different minimum $\chi^2$ of $3 < \chi_{\text{min}} < 6$, we consider each solution equally possible. All three SED models are able to produce $H - [3.6] > 4.5$ and require extreme conditions in the galaxies: either extremely dusty of $A_V > 7$ or even $A_V = 16$ or very massive galaxies at $z > 4.5$, both of which are very rare in current extragalactic surveys.

3.2. Extremely Dusty Galaxies at $z < 3$?

In the first solution, a galaxy with the Calzetti extinction of $A_V \sim 16$ at $z = 0.8$ can have $H - [3.6] > 4.5$. At $z = 0.8$, the IRAC 3.6 $\mu$m band probes the rest-frame K band. Our sources have 3.6 $\mu$m flux densities of $f_{3.6} = 0.6$–1.5 $\mu$Jy, implying that their stellar masses are less than $5 \times 10^9 M_\odot$. Most galaxies with such a small stellar mass at $z = 0.8$ are blue galaxies with no dust extinction. M82 is a dusty galaxy with a lower stellar mass

![Figure 2. Likelihood contours as a function of redshift and dust extinction $A_V$ for the best-fit SED of ERS-1. SED fitting for the remaining objects yields the same solutions. The left panel is the contour with the 1 Gyr stellar population model and the Calzetti extinction and the right panel is with the SMC extinction. The 1 Gyr stellar population model with the Calzetti extinction of $A_V = 3.6$ is also the best fit for GOODS 850-5 at $z = 4.05$.](image-url)
of 4 × 10^9 M_☉, with heavy dust obscuration (5 < A_V < 51) only occurring in its center (Beirão et al. 2008). The whole M82 appears much bluer than our objects. The H – [3.6] color at z = 0.8 is equivalent to the rest-frame I – K color. M82 has I – K = 0.82 (Dale et al. 2007), because most stars in the disk of M82 are in the outside of its dusty region. Thus an object like M82 at z = 0.8 would be detected in the ERS H-band imaging. This solution, however, requires that the whole galaxy should be in heavy obscuration. Only ULIRGs have such an obscured morphology. Using M82 central region SEDs, we predict that the MIPS 24 μm flux densities for the first three sources would have f_{24} = 50–70 μJy, well above the FIDEL MIPS 24 μm limiting flux density. Only ERS3 is marginally detected at 24 μm with f_{24} = 39 μJy; the rest are not detected at 24 μm. We argue that this scenario is least possible.

The second solution is the template with the SMC extinction of A_V = 7–8 at z = 2 – 2.2. There are many dust-obscured galaxies (DOGs) identified at z ∼ 2 (Houck et al. 2005; Dey et al. 2008; Bussmann et al. 2009). Several groups (Houck et al. 2005; Yan et al. 2007; Huang et al. 2009) performed mid-infrared spectroscopy for DOGs and detected a very strong silicate absorption feature at 9.8 μm in their spectra, indicating a very heavy dust extinction. Bussmann et al. (2009) took high-resolution H-band imaging of these sources in the Bootes field with NICMOS on HST to study their rest-frame optical morphologies. We identified these DOGs in the Bootes IRAC photometry catalog (Ashby et al. 2009), and found that DOGs were generally red with 1.5 < H – [3.6] < 3.3, and luminous at 3.6 μm with f_{3.6} = 5–60 μJy. The four sources in this study are much fainter at 3.6 μm and have a much redder color of H – [3.6] > 4.5. On the other hand, the DOGs in Bussmann et al. (2009) have a 24-to-8 μm flux ratio of f_{24}/f_{8} = 40–350. If the four sources were indeed fainter DOGs at z ∼ 2, they should have a 24 μm flux density of f_{24} > 120 μJy, much higher than the 24 μm limiting flux density in GOODS-South. Based on much redder H – [3.6] and fainter 24 μm flux, we argue that these objects are at higher redshifts than the DOGs at z ∼ 2.

3.3. Massive Galaxies at z > 4.5?

The 1 Gyr SSP template with the Calzetti extinction of A_V = 0.8 at z ∼ 5.7 can also fit the SEDs of the four objects, very similar to the best-fit template for GOODS 850-5. In this scenario, the red H – [3.6] is mainly due to the Balmer/4000 Å jump shifting between H and 3.6 μm bands at z > 4. Figure 3 shows that the old stellar template fits to SEDs of the four objects. The resulting photometric redshifts have a large error of 0.4 < σ(z) < 1.1. We argue that the four objects are at the same redshifts. Thus, by adopting the best σ(z) in the four objects, these objects should be at z > 4.5 at the 3σ level.

ERS-3 is detected at 250 and 350 μm, and thus has a very strong FIR emission, very similar to GOODS 850-5 (Huang et al. 2010). The best-fit SED models for both GOODS 850-5 and ERS-3 are old stellar population models. We propose a two-component SED model to reconcile the old stellar population and FIR emission in these objects: an old stellar population and a very dusty star-forming component. The star-forming component is so dusty, similar to those dusty galaxies detected at z ∼ 2 (Houck et al. 2005; Yan et al. 2007; Dey et al. 2008; Huang et al. 2009), that its optical/NIR SED is dominated by the old stellar population component. For example, a dusty component with the same stellar mass and A_V = 6 at z > 5 would only contribute 10% increase at 8 μm and much lower percentage in the shorter IRAC bands. Assuming a typical dust temperature of T_dust = 40 K and redshift of z = 5.7, we calculate the FIR luminosity for ERS-3 as log(L_{FIR}/L_☉) = 13.1. The FIR-to-radio flux ratio is about q = 2.26, consistent with q values for submillimeter galaxies at z > 4 (Huang et al. 2011). The remaining three objects are not detected by Herschel/SPIRE, but may still be IR luminous galaxies with just log(L_{FIR}/L_☉) < 13.1.

The SSP model fitting also yields stellar masses of log(M_*/M_☉) = 10.6–11.2 for our sources (Figure 3). Spectroscopic confirmed galaxies at z ∼ 5.7 including both Lyman-break (LBGs) and Lyα (LAE) galaxies have a typical stellar mass of log(M_*/M_☉) ≤ 10 (Yan et al. 2006; Lai et al. 2007; Younger et al. 2007; Richard et al. 2011). Recently Marchesini et al. (2010) argued that very massive galaxies were already formed at 3 < z < 4. Theoretically, Li et al. (2007) argued that QSOs at z > 6 resided in a massive halo of M ∼ 8 × 10^{12} M_☉, and stellar masses for their host galaxies can be as high as 10^{12} M_☉. We have another piece of evidence consistent with these systems being massive. ERS-1 is also an X-ray source detected in the Chandra 2 Ms survey (Alexander et al. 2003). It has X-ray flux densities of f_{0.5–2keV} = 7.55 ± 2.14 × 10^{-17} erg s^{-1} cm^{-2} and f_{2–8keV} = 6.50 ± 1.50 × 10^{-16} erg s^{-1} cm^{-2}. The hard X-ray luminosity for this source is
$L_{2−8keV} = 1.6 \times 10^{44} \text{erg s}^{-1}$ at $z_p = 5.7$ assuming no absorption correction. Its X-ray-to-optical-flux ratio ($f_x/f_\nu$) is higher than 60 and the hardness ratio is $\sim 1$, thus ERS-1 is an obscured type-II QSO. A typical black hole mass for such a QSO at $z = 3−6$ is $10^9$ to $10^{10} M_\odot$ (Netzer 2003; Shemmer et al. 2004; Fan et al. 2006). Assuming a typical Hz FWHM of 2000 km s$^{-1}$ for a QSO, we convert the $L_{2−8keV}$ to black hole mass for ERS-1 as $M_{BH} = 5 \times 10^9 M_\odot$ using the relation proposed by Sarria et al. (2010). Trakhtenbrot & Netzer (2010) argued that a host galaxy with $10^9 M_\odot$ black hole has a typical stellar mass of $M_\star \sim 10^{11} M_\odot$, consistent with the stellar mass we derived for ERS-1.

4. SUMMARY AND DISCUSSION

We identified four IRAC sources in the GOODS-South field with extremely red color of H − [3.6] > 4.5. The only known source with a similar H − [3.6] color is GOODS 850-5, an SMG in the GOODS-North field. We argue that the four sources must be at the same redshift based on the following facts: they have similar rest-frame optical/NIR SEDs; and they are spatially very close to each other with a mean angular distance $\sim 1.5$. Only three types of templates can produce H − [3.6] > 4.5: a very dusty template with the Calzetti extinction of $A_V = 16$ mag at $z = 0.8$, a very dusty templates with the SMC extinction of $A_V = 8$ mag at $z = 2.0$, and a 1 Gyr SSP model with $A_V \sim 0.8$ at $z = 5.7$. By comparing the four objects with local dustily galaxies and DOGs at $z \sim 2$, we argue that they are unlikely dusty galaxies at $z = 0.8$ or $2.2$ based on absent strong 24 $\mu$m emission. The old stellar population model at $z > 4.5$, with the best fit at $z = 5.7$, remains a possible solution for the four sources. One of our sources, ERS-3, is also detected by Herschel at 250 $\mu$m and 350 $\mu$m, yielding log($L_{FIR}/L_\odot$) = 13.2. We propose a two-component SED model for these sources: an old SSP component dominating their optical-to-MIR SEDs and a very dusty star-forming component mainly contributing to their FIR SEDs. The SED fitting yields stellar masses of log($M_\star/M_\odot$) = 10.6–11.2 for the four sources. One source, ERS-1, is also a type-II X-ray QSO with $L_{2−8keV} = 1.6 \times 10^{44} \text{erg s}^{-1}$. Based on the $M_{BH}−M_{bulge}$ relation for high-z QSOs, ERS-1 should have a massive bulge of log($M_\star/M_\odot$) = 11. One of the four sources is an X-ray QSO and another one is a HyperLIRG, suggesting a galaxy-merging scenario for the formation of these massive galaxies at high redshifts.

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Facilities: Spitzer(IRAC), HST(STIS), CXO(ASIS)

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