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Webb's PEARLS: Transients in the MACS J0416.1−2403 Field

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Abstract

With its unprecedented sensitivity and spatial resolution, the James Webb Space Telescope (JWST) has opened a new window for time-domain discoveries in the infrared. Here we report observations in the only field that has received four epochs (over 126 days) of JWST NIRCam observations in Cycle 1. This field is towards MACS J0416.1−2403, which is a rich galaxy cluster at $z = 0.397$ and is one of the Hubble Frontier Fields. We have discovered 14 transients from these data. Twelve of these transients happened in three galaxies (with redshifts $z = 0.94$, 1.01, and 2.091) crossing a lensing caustic of the cluster, and these transients are highly magnified by gravitational lensing. These 12 transients are likely of a similar nature to those previously reported based on the Hubble Space Telescope (HST) data in this field, i.e., individual stars in the highly magnified arcs. However, these twelve could not have been found by the HST because they are too red and too faint. The other two transients are associated with background galaxies ($z = 2.205$ and 0.7093) that are only moderately magnified, and they are likely supernovae. They indicate a de-magnified supernova surface density of $\sim$0.5 arcmin^{-2} integrated up to $z \approx 2$ when monitored at the time cadence of a few months. Such a high surface density is achieved at the $\sim$3–4 μm survey limit of AB $\sim$ 28.5 mag, which, while beyond the capability of HST, can be easily reached by JWST.

1. INTRODUCTION

New capabilities in multi-messenger and time-domain astronomy will open outstanding vistas for discovery, as highlighted, for example, in the Decadal Survey on Astronomy and Astrophysics 2020 (Astro2020)[1]. A core challenge is in localizing sources on the sky and in redshift, with the primary technique being searches for electromagnetic counter-

[1] https://nap.nationalacademies.org/resource/26141/interactive/

parts, which calls for observatories with the best flux sensitivity and angular resolution possible.

Until recently, one of the leading observatories for this purpose was the Hubble Space Telescope (HST), which had many successes. For example, it has found high-redshift supernovae, especially those of type Ia, which constrain cosmological models. In many cases, these observations were integrated with large, general-purpose extragalactic surveys (e.g., Riess et al. 2004; Amanullah et al. 2010; Suzuki et al. 2012; Riess et al. 2018). Observations of high-redshift clusters have been important for increasing yields (e.g., Dawson et al. 2009; Hayden et al. 2021) while observations of low-redshift clusters have led to the first discovery of a multiply imaged supernova (at $z = 1.49$) due to gravitational lensing (Kelly et al. 2015), which provides a new route to constrain H_0 through time delay (Kelly et al. 2023). For another example, a novel type of transient phenomena — caustic-crossing transients — has been identified through HST observations (Kelly et al. 2018; Rodney et al. 2018; Chen et al. 2019; Kaurov et al. 2019). These are individual stars in highly magnified background galaxies lying very close to the critical curve of the lensing cluster, which are further magnified — temporarily — by the intracluster stars that serve as microlenses. These have given us a completely unexpected method to study individual stars at cosmological distances.

The advent of the James Webb Space Telescope (JWST) has brought dramatically better opportunities, due to its more than an order of magnitude increase of efficiency relative to HST. The Prime Extragalactic Areas for Reionization and Lensing Science program (PEARLS; Windhorst et al. 2023), one of the programs under the JWST Interdisciplinary Scientists' Guaranteed Time Observations (GTO), has a major time-domain science component. One of its fields is MACS J0416.1−2403 (hereafter M0416), which is a lensing cluster at $z = 0.397$ and one of the Hubble Frontier Fields (HFF; Lotz et al. 2017), where several caustic-crossing transients have been found with HST near two caustic-straddling arcs. Rodney et al. (2018) discovered two fast transients in an arc at $z = 1.0054$, which are collectively nicknamed by the authors as "Spock." The transients in this strongly lensed galaxy are consistent with being supergiant stars with temperatures between 3500 K and 18000 K, as shown in Diego et al. (2023). Chen et al. (2019) and Kaurov et al. (2019) identified a transient of similar nature in another arc at $z = 0.94$, which is named "Warhol." In addition, the ultra-deep, UV-to-visible HST program "Flashlights" detected two high-significance caustic transients in the Spock arc and four in the Warhol arc (Kelly et al. 2022). It is expected that these highly lensed regions are constantly producing caustic transients.

To take advantage of these opportunities with JWST, PEARLS has incorporated three epochs of NIRCam observations of M0416 in its design. We expect that these data are particularly powerful for detecting red supergiant stars at redshifts $z \gtrsim 1$ because they are bright at $\lambda \gtrsim 2\ \mu$m. The design is also motivated by the possibility of detecting individual Population III stars through caustic transits at $z > 7$ (Windhorst et al. 2018). Another JWST GTO program, the CAnadian NIRISS Unbiased Cluster Survey (CANUCS; Willott et al. 2022), also has one separate epoch of NIRCam observations on this cluster. All these data have been taken, which makes M0416 the only field in JWST Cycle 1 that has four epochs of NIRCam observations. For this reason, M0416 is the best region in the sky to date for studying infrared transients.

We have carried out a transient search using these unique data. The search has gone beyond the aforementioned two arcs, as we also intend to assess the general infrared transient rate in less magnified regions at depths that have never been probed before. This paper is the first in a series on this subject and presents the overview of the transients found in this field. The paper is organized as follows. The NIRCam observations and data are described in Section 2. The transient search is detailed in Section 3. We discuss the transients in Section 4 and conclude with a summary in Section 5. All magnitudes are in the AB system. All coordinates are in the ICRS frame (equinox 2000).

2. OBSERVATIONS AND DATA

The four epochs of NIRCam observations all used the same eight bands, namely, F090W, F115W, F150W, and F200W in the "short wavelength" (SW) channel and F277W, F356W, F410M, and F444W in the "long wavelength" (LW) channel, respectively. The native NIRCam pixel scales are $0\farcs031$ pix^{-1} in the SW channel and $0\farcs063$ pix^{-1} in the LW channel. As the SW channel is made of four detectors, the observations used the `INTRAMODULEBOX` dithers to cover the gaps in between. The PEARLS observations adopted the `MEDIUM8` readout pattern with "up-the-ramp" fitting to determine the count rate, while those of CANUCS used a combination of the `SHALLOW4` and `DEEP8` patterns. The total exposure times, dates of observation, and 5 σ depths of these observations are summarized in Table 1.

NIRCam has two nearly identical modules ("A" and "B") that subtend two adjacent, square fields. As the spatial orientations of the JWST instruments vary in time on an annual basis, these two fields cannot both be on the same region in the sky within a year. For this reason, all four epochs of NIRCam observations were designed to center the B module on the cluster, leaving the A module mapping different regions in the flanking area. In this transient study, we only use the module B data because only these are spatially overlapped.

The data were retrieved from the Mikulski Archive for Space Telescopes (MAST). Reduction started from the so-called Stage 1 "uncal" products, which are the single exposures from the standard JWST data reduction pipeline after Level 1b processing. We further processed these products using the version 1.9.4 pipeline in the context of `jwst_1063.pmap`. A few changes and augmentations were made to the pipeline to improve the reduction quality; most importantly, these included enabling the use of an external reference catalog for image alignment and implementing a better background estimate for the final stacking. The astrometry of the single exposures was calibrated using the

Table 1. M0416 NIRCam Observation Summary

Epoch Start UT	Filter	Exptime (s)	Depth 5σ
Ep1	F090W	3779.343	28.45
2022 Oct 7 08:06:05	F115W	3779.343	28.48
(0.0 days)	F150W	2920.401	28.48
(PA = 293°)	F200W	2920.401	28.69
	F277W	2920.401	29.83
	F356W	2920.401	29.91
	F410M	3779.343	29.38
	F444W	3779.343	29.58
Ep2	F090W	3779.343	28.49
2022 Dec 29 16:00:36	F115W	3779.343	28.51
(83.4 days)	F150W	2920.401	28.51
(PA = 33°)	F200W	2920.401	28.72
	F277W	2920.401	29.88
	F356W	2920.401	29.93
	F410M	3779.343	29.39
	F444W	3779.343	29.59
Ec	F090W	6399.115	28.63
2023 Jan 11 20:24:42	F115W	6399.115	28.64
(96.7 days)	F150W	6399.115	28.82
(PA = 49°)	F200W	6399.115	29.02
	F277W	6399.115	30.14
	F356W	6399.115	30.19
	F410M	6399.115	29.50
	F444W	6399.115	29.70
Ep3	F090W	3779.343	28.48
2023 Feb 10 09:12:32	F115W	3349.872	28.41
(126.1 days)	F150W	2920.401	28.49
(PA = 71°)	F200W	2920.401	28.69
	F277W	2920.401	29.84
	F356W	2920.401	29.86
	F410M	3349.872	29.21
	F444W	3779.343	29.47

NOTE—The 5σ depths were measured from the RMS map within circular apertures of $0\farcs2$ radius. PA is the angle of the detector y axis projected on the sky in degrees east from north.

GAIA 3rd Data Release. These single images were projected onto the same grid and were stacked in each band and in each epoch. We produced two versions of stacks, one at the pixel scale of $0\farcs06$ (hereafter the "60mas" version) and the other at the scale of $0\farcs03$ (the "30mas" version), to best match the native pixel scales in the LW and the SW channels, respectively. The mosaics are in surface brightness units of MJy sr^{-1}. The AB magnitude zeropoints are 26.581 and 28.087 for the 60mas and the 30mas stacks, respectively. Figure 1 shows the composite color image using the data from all these four epochs. For convenience, hereafter we refer to the three epochs from the PEARLS program as Ep1, Ep2 and Ep3, respectively, where "p" stands for "PEARLS"; the epoch from the CANUCS program, which was in between Ep2 and Ep3, is referred to as Ec ("c" stands for "CANUCS").

3. TRANSIENT DISCOVERIES

3.1. *Search method*

The search for transients was done in the usual way by detecting positive peaks on difference images between epochs. Thanks to the excellent image alignment and stable image quality, we were able to form the difference images by direct subtraction, for which we used the 60mas images. Due to the intense human labor in the visual inspection step (see below), this work is limited to these pairs of difference images: Ep1 − Ep2 for the search of decaying sources in Ep1, Ep2 − Ep1 for new sources appearing in Ep2, and Ep3 − Ep1 for new sources appearing in Ep3. Ec was not used to initiate transient searches, as it was only 13.3 days after Ep2; however, it was used when studying the light curves of the identified transients. When building a difference image, its "root mean square" (RMS) map was also constructed by adding the error maps of the parent images in quadrature. As compared to the SW images, the LW images are less affected by defects and therefore their difference images are cosmetically cleaner. We chose to use the F356W band as the basis of our search because its data are the deepest.

The 60mas version was used in the initial search. SExtractor (Bertin & Arnouts 1996) was run on the F356W difference images between epochs. The RMS maps were used in the process to estimate the signal-to-noise ratios (S/N) of the peaks in the difference images. Only the peaks that have $\mathrm{S/N} \geq 5$ were further considered. This left thousands of peaks in each difference image, which were then visually inspected. Not surprisingly, the vast majority of these peaks are not transient objects but are residuals caused by imperfect subtraction of bright stars and galaxies due to two reasons: (1) the values of the pixels occupied by bright objects fluctuate over different epochs because of Poisson noise, which often results in positive peaks accompanied by negative peaks in a difference image; (2) the position angle of the point spread function (PSF) is different in different epochs (due to the different field orientations), which leads to spurious sources around bright objects that appear in different positions in different epochs. After this visual inspection step, only a few tens of transient candidates survived.

To ensure their reliability, we further required that the selected transients should be detected at $\mathrm{S/N} \geq 5$ in the difference image of at least one more band in addition to F356W. Under this requirement, we obtained a total of 14 robust transients.

3.2. *Descriptions of the transients and their photometry*

Our sample includes seven transients in the Warhol region, four in the Spock region, one in yet another arc, and two in other regions. Their locations are indicated in Figure 1. These objects and their photometry are described below. In most cases, these sources are embedded in a highly non-uniform background and/or are affected by contamination from nearby objects, and PSF fitting had to be used to obtain reliable photometry. For this purpose, the 30mas images are more appropriate. To be consistent, we use PSF

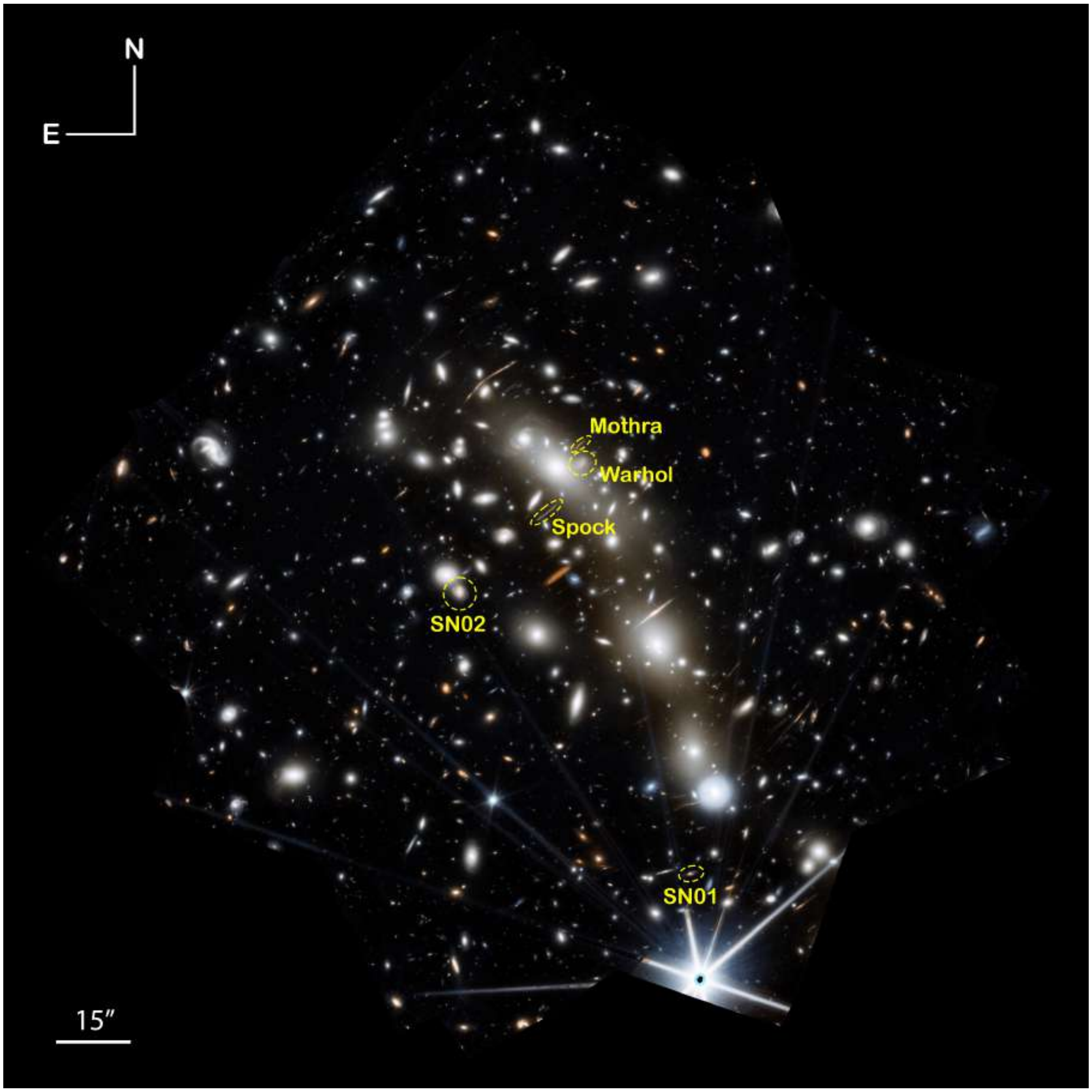

Figure 1. Color composite image of M0416 using the data from four epochs of NIRCam observations as described in the text. The color scheme is F090W+F115W+F150W as blue, F200+F277W as green, and F356W+F410M+F444W as red. The regions where the transients are found are also marked.

fitting for all objects on the 30mas images, and the detailed process is explained in the Appendix.

3.2.1. *Transients in the Warhol region*

Figure 2 shows the positions of the seven transients discovered in this region. The first three letters in their IDs indicate the difference images on which they were first detected in our process; for example, "Dc2" stands for the difference image constructed by subtracting the Ep2 image from the Ec image, and so on. The letter "W" indicates that these are in the Warhol region. The photometric results are listed in Table 2. Figure 3 shows three of them (`D21-W1`, `D21-W2` and `D21-W3`) that were seen in multiple epochs, while Figure 4 shows the other four (`Dc2-W4`, `D31-W5`, `D31-W6`, `D31-W7`) that were only visible in a single epoch.

• `D21-W1` This transient was visible in Ep1, reached the maximum brightness in Ep2, became fainter in Ec, and further declined in brightness in Ep3 but still remained visible. It faded more rapidly in the red bands than in the blue ones. At its peak ($m_{277} = 27.10$ mag), it was the brightest among all transients in this region. As it was visible in all epochs, its photometry was done in each epoch individually.

• `D21-W2` This transient was invisible in Ep1, appeared in Ep2 and slowly varied in the following two epochs. Interestingly, its behaviors in the SW and the LW bands differed: while it decayed with time in the LW bands, it became much brighter in the SW bands in Ep3, especially in the two bluest bands. The photometry was done on the difference images between these epochs and Ep1 (i.e., the D21, Dc1 and D31

Table 2. Catalog of transients in the Warhol region.

	R.A.	Decl.	Epoch	F090W	F115W	F150W	F200W	F277W	F356W	F410M	F444W
D21-W1	64.03695	−24.06725	Ep1	29.74±0.44	28.89±0.13	28.15±0.06	27.90±0.05	27.65±0.07	27.97±0.11	28.05±0.12	28.46±0.13
			Ep2	29.41±0.19	28.68±0.10	27.92±0.05	27.34±0.04	27.10±0.05	27.19±0.05	27.42±0.06	27.56±0.06
			Ec	29.09±0.22	28.96±0.12	28.28±0.06	27.78±0.04	27.61±0.06	27.65±0.06	27.79±0.07	28.08±0.08
			Ep3	29.53±0.34	29.36±0.35	29.03±0.14	29.00±0.16	29.10±0.30	>29.93*	>29.51*	>29.73*
D21-W2	64.03674	−24.06725	Ep2	29.43±0.21	>29.28	28.88±0.16	28.99±0.17	28.37±0.10	28.11±0.09	28.08±0.11	28.83±0.15
			Ec	29.26±0.17	29.07±0.15	29.21±0.20	29.49±0.25	28.53±0.11	28.40±0.12	28.25±0.15	28.78±0.18
			Ep3	28.33±0.08	28.31±0.08	28.55±0.11	28.89±0.16	29.19±0.23	28.67±0.16	28.72±0.20	29.09±0.21
D21-W3	64.03665	−24.06728	Ep2	>29.31	>29.28	29.72±0.32	28.88±0.14	28.67±0.16	28.42±0.12	28.69±0.26	29.10±0.23
			Ec	>29.40	>29.38	30.13±0.46	29.78±0.33	29.09±0.23	28.66±0.14	28.59±0.21	28.77±0.17
Dc2-W4	64.03655	−24.06731	Ec	>28.89*	>28.87*	29.00±0.19	28.18±0.11	27.38±0.07	27.04±0.06	27.28±0.06	27.36±0.07
D31-W5	64.03668	−24.06732	Ep3	>29.32	>29.29	>29.24	29.28±0.22	28.75±0.18	28.62±0.16	28.99±0.31	29.62±0.39
D31-W6	64.03654	−24.06744	Ep3	>29.32	>29.29	29.13±0.17	28.56±0.09	28.32±0.13	28.16±0.10	28.17±0.16	28.07±0.11
D31-W7	64.03650	−24.06736	Ep3	>29.32	29.86±0.34	29.71±0.30	28.78±0.16	28.50±0.15	28.31±0.12	28.64±0.20	28.77±0.18

NOTE—The R.A. and Decl. coordinates are in decimal degrees for the J2000.0 equinox. The magnitudes are based on the PSF-fitting results. The upper limits are measured within 11×11 pixels (to match the size of the PSF fitting area) centered at the source location on the error maps. The limits labeled with $*$ are 5σ upper limits (appropriate for the measurements in the original image where the background is high and non-uniform), otherwise 2σ (more appropriate for the measurements in the difference images where the background is largely subtracted).

images), as this would offer a more reliable determination of the background.

• `D21-W3` This transient was only $0''.28$ away from `D21-W2` and was also invisible in Ep1. It appeared in Ep2 in F150W and redder bands. It was much weaker in Ec and barely (if at all) visible in Ep3. The photometry was done on the difference images between all other epochs and Ep1. The decline in brightness from Ep2 to Ec is very obvious in the blue bands. The F444W photometry weakly suggests that it might be slightly brightened from Ep2 to Ec, however this is inconclusive due to the large errors. The extracted signals in Ep3 all have $\mathrm{S/N} < 2$, which we consider as non-detections.

• `Dc2-W4` This event appeared as a sudden brightening in Ec, particularly in the LW bands. As mentioned earlier, Ec was not used to initiate the transient search; this event was found on the difference images involving Ec when inspecting other transients in the Warhol region. While there seems to be a "source" in other epochs at this location, there is no detectable signal in the difference images in between Ep1, Ep2 and Ep3. This means that the event happened only in Ec and that it left no trace in any other epochs, including Ep2, which was only 13.3 days apart. The photometry was done on the difference images between Ec and Ep1 (i.e., the Dc1 images).

• `D31-W5` This transient was only seen in Ep3, as it was only visible in the difference images involving Ep3. It was very close to `D21-W3` but was a different transient. It was invisible in the three bluest bands. The photometry was done on the difference images between Ep3 and Ep1 (the D31 images).

• `D31-W6` and `D31-W7` These two transients were also only seen in Ep3. Like `D31-W5`, the photometry was done on the difference images between Ep3 and Ep1 (the D31 images).

3.2.2. *Transients in the Spock region*

Figure 5 shows the positions of the four transients in this region. Due to the high brightness of this arc, these transients can only be revealed in the difference images and none of them are clearly seen in the original images. The designation of their IDs follows the convention as in §3.2.1, with the exception that "S" is used to indicate that these transients are in the Spock region. Figures 6 to 9 show the details of these transients. Their photometry (except for `D23-S3`, see below) is presented in Table 3.

• `D21-S1` This transient is best detected in the difference images between Ep2 and Ep1 (the D21 images), but is only seen in the LW bands. It becomes significantly weaker in the difference images between Ec and Ep1 (the Dc1 images), and almost completely disappears from those between Ep3 and Ep1 (the D31 images). All this indicates that it reached the maximum in Ep2 and then faded. Assuming that it was invisible in Ep1, we obtained its magnitudes in Ep2 and Ec by photometry on the difference images between Ep2 and Ep1 (D21) and those between Ec and Ep1 (Dc1).

• `D21-S2` This transient is detected in the difference images involving Ep2 but not without. Therefore, it is reasonable to assume that this event was caught in Ep2 only. The photometry was done on the difference images between Ep2 and Ep3 (i.e., the D23 images) because they offer a cleaner background than others (e.g., the D21 images).

• `D23-S3` This transient is best detected in the difference images between Ep2 and Ep3 (D23). It appears in the D23 images in F150W through F410M, is barely visible in F444W, and is invisible in F115W and F090W. This transient presents a complicated case that is difficult to understand. First of all, it seems to be an elongated system in the D23 F356W image. In the D23 F200W and F150W images, which have better resolution, this elongated structure is resolved into two components. However, it does not maintain such a two-component structure (or the elongated morphology) consistently in all bands: one of the components (the

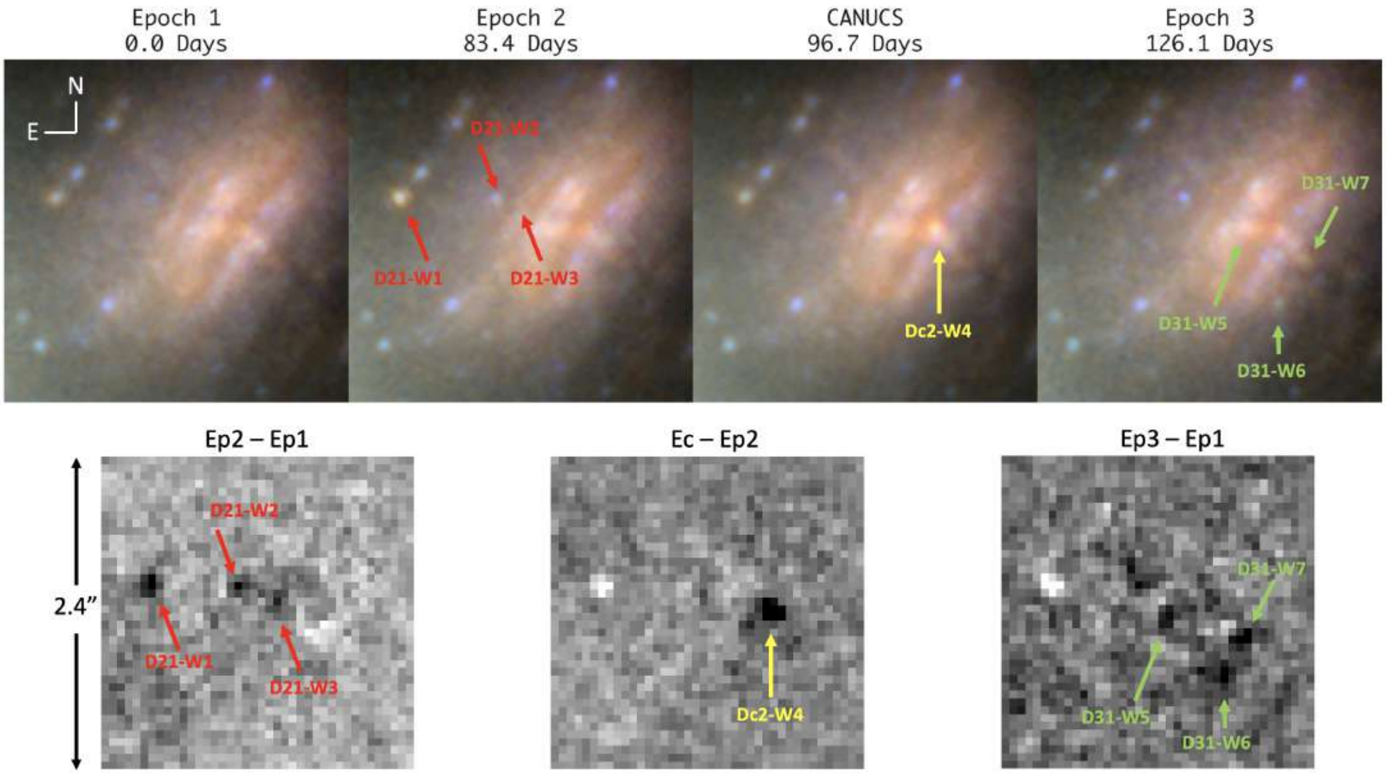

Figure 2. Locations of the transients found in the Warhol region. The upper panel shows the color images of this region in the four epochs, while the lower panel shows the inverted F356W difference images of the same region in between relevant epochs that led to the discovery of these transients as labeled. All these images are 2″.4 on a side and are oriented north-up and east-left.

Table 3. Catalog of transients in the Spock arc region

	R.A.	Decl.	Epoch	F090W	F115W	F150W	F200W	F277W	F356W	F410M	F444W
D21-S1	64.03847	−24.06984	Ep2	>29.13	>29.17	>29.14	>29.36	28.55±0.11	28.56±0.09	28.74±0.17	29.00±0.14
			Ec	>29.17	>29.21	>29.24	>29.44	29.17±0.16	29.31±0.17	29.06±0.25	29.83±0.27
D21-S2	64.03889	−24.07017	Ep2	>29.13	>29.17	29.65±0.27	29.13±0.17	28.33±0.10	28.61±0.12	29.12±0.34	29.33±0.27
D23-S3	64.03874	−24.07004									
D31-S4	64.03836	−24.06978	Ep3	>29.11	29.95±0.29	29.86±0.33	29.06±0.17	28.55±0.13	28.44±0.09	28.68±0.20	28.49±0.11

NOTE—Similar to 2, but for the transients in the Spock arc region.

southern one) is missing from the D23 F277W and F410M images. Second, in the difference images between Ep2 and Ep1 (D21), only the southern component appears, and it only appears in F200W and F150W. Taking the above at the face value, one would infer the following picture: (1) D21-S3 was made of two components; (2) the northern one maintained its brightness from Ep1 to Ep2 and then decayed (not visible in the D21 images but showing up in the D23 images); (3) the southern component brightened in Ep2 but only in F150W and F200W (in the D21 images, only visible in F150W and F200W), and then decayed; (4) however, this southern component maintained the brightness from Ep1 through Ep3 in F277W, F356W and F410M. The last point is inconsistent with the observation that the southern component seems to be present in the D23 F356W image. It is possible to attribute this inconsistency to the weakness of the signals. We attempted PSF fitting on the two components in the D23 images, however the fitting failed in all bands. We have to give up photometry on this transient.

• `D31-S4` This transient is only detected in the difference images involving Ep3, implying that it appeared in Ep3. It is very close to `D21-S1` (only 0″.39 apart), which already decayed and was invisible in Ep3. The photometry was done on the difference images between Ep3 and Ep1 (D31).

We note that the number of transients (four) observed in this arc in the four epochs is consistent with expectations made for JWST for this particular arc. In Diego et al. (2023), the authors find that due to microlensing, one expects between 1–5 transients per pointing in the Spock arc when reaching ∼29 mag.

3.2.3. *A transient in yet another arc*

Table 4. Photometry for the transient "Mothra" in an arc at $z = 2.091$.

R.A.	Decl.	Epoch	F090W	F115W	F150W	F200W	F277W	F356W	F410M	F444W
64.03676	−24.06625	Ep1	28.19±0.19	28.12±0.17	28.11±0.24	28.07±0.25	27.96±0.24	27.96±0.25	27.89±0.23	27.88±0.22
		Ep2	28.19±0.19	28.12±0.17	28.11±0.24	27.92±0.23	27.77±0.21	27.46±0.16	27.47±0.17	27.49±0.16
		Ec	28.19±0.19	28.12±0.17	27.92±0.21	27.66±0.18	27.46±0.16	27.37±0.15	27.29±0.14	27.27±0.13
		Ep3	28.19±0.19	28.12±0.17	27.88±0.20	27.76±0.20	27.40±0.15	27.36±0.15	27.24±0.14	27.24±0.13

There is one transient identified on an arc at $z = 2.091$ (Bergamini et al. 2022) where no previous transient has been reported. Dubbed "Mothra," this transient is discussed in detail in Diego et al. (2023b, to be submitted). Here we only present its discovery. Figure 10 shows the details of this transient. Its location is labeled on the color images, which points to a bright knot (the faintest among the five knots) on the arc that was visible in all four epochs. This transient is best explained by the intrinsic variability of a red supergiant star that is being magnified by a dark milli-lens (Diego et al. 2023, to be submitted).

The transient is best seen in the difference images between Ep3 and Ep1 (D31) and as well as in those between Ec and Ep1 (Dc1), where it shows up as a strong, red source decreasing the amplitude towards the blue end. It is even visible in the difference images between Ec and Ep2 (Dc2; 13.3 days apart), albeit being much weaker. It is almost invisible in the difference images between Ep3 and Ec (D3c; 29.4 days apart). In other words, this knot was slowly increasing in brightness and reached the maximum at around Ec (96.7 days between Ep1 and Ec), and it more or less kept at the maximum through Ep3 (29.4 days between Ec and Ep3).

Since this transient event was caused by the variability of a source that was visible in all epochs, ideally its photometry should be done on the images taken in each epoch. As it is almost blended with the nearby (and brighter) knot, one should do PSF fitting on both simultaneously. However, we were only able to obtain reasonable PSF fitting results in Ep1 (see the Appendix for details). The procedure failed in other epochs, mostly because the light of brightened transient blended with the nearby knot more severely. Therefore, we performed PSF fitting on the difference images between Ep1 and other epochs (see Figure 10) and then added the excess fluxes extracted in this way to the Ep1 SED to obtain the SEDs in other epochs. The results are presented in Table 4 and are also shown in the bottom row in Figure 10.

3.2.4. *Two likely supernovae*

There were two transients associated with galaxies that are only moderately magnified. Both of them were detected in multiple epochs, and neither was seen in the HFF data. Based on their light curves, we believe that they are SNe. Their physical interpretations will be detailed in a forthcoming paper (Wang et al., in prep.). Here we provide a brief description of their discovery and photometric properties. The photometry is presented in Table 5.

• `SN01` We reported this event in (Yan et al. 2023) based on the data from Ep1 and Ep2. Figure 11 shows the color images of the transient and its vicinity in the four epochs. The transient appeared as a blue source in Ep1 and then became very red in the subsequent epochs. From the difference images in between epochs, we can see that its red light (F200W and redder) reached the maximum in Ep2. It was very close to an irregular galaxy, which presumably is the host. The CANUCS NIRISS slitless spectroscopy shows that this galaxy is at $z = 2.205$. Based on the latest lens model of this cluster (Diego et al., in prep.), the galaxy is amplified by a factor of $\mu = 5.37$. As the transient was visible in all epochs, its photometry should be done on the images in individual epochs. To minimize the impact of the contamination from the host galaxy, the photometry was done by PSF fitting. The results are also shown in Figure 11.

• `SN02` This transient was found within a spiral galaxy at $z = 0.7093$ (redshift based on (Caminha et al. 2017)), which is amplified by $\mu = 2.07$ based on the same lens model. It was invisible in Ep1 and appeared in Ep2. From the difference images in between the four epochs, it seems that this transient was the brightest in most bands in Ep2 and then slightly decayed in Ec and Ep3. The photometry in Ep2, Ec and Ep3 was done on the difference images between Ep2 and Ep1 (D21), Ec and Ep1 (Dc1), and Ep3 and Ep1 (D31). In these difference images, its neighbourhood is still affected by the strong residuals due to the imperfect subtraction of the host galaxy bulge. Our PSF-fitting photometry reduced the contamination.

4. DISCUSSION

The NIRCam data used here were produced by only half of the NIRCam field of view (by its module B). Due to the different field orientations at different times, the area overlapped in all four epochs amounts to only 3.98 arcmin^2. Our data result in 14 robust transients, the largest number of transients ever found within such a small area. There are two reasons for this high transient "production" rate. First, the high sensitivity of NIRCam has allowed us to search for transients to an unprecedented depth. The vast majority of our transients were fainter than 27.0 mag even at their peaks and were fainter than 28.0 mag most of the time in most bands. The PEARLS observations had exposure times of ∼0.8–1 hours per band per epoch, and the data have reached the 5 σ limits of ∼28.5–30.0 mag (within $0''.2$ radius aperture), which are sufficient for us to validate the transients in multiple bands. Second, M0416 has included two regions extremely magnified by the cluster, the Warhol and the Spock arcs, which are known to have produced a number of caustic transients in the previous studies with HST. Both arcs are at relatively low redshifts ($z \approx 1$), which facilitates the detection of luminous stars in them. In our data spanning 126 days, these two regions contribute seven and four transients, respectively, making them the most fertile transient "factories." In addition,

Table 5. Photometry for the two SNe

	R.A.	Decl.	Epoch	F090W	F115W	F150W	F200W	F277W	F356W	F410M	F444W
SN01	64.02954	−24.09022	Ep1	26.84±0.05	26.85±0.04	27.25±0.03	27.73±0.04	28.29±0.07	>29.82*	>29.24*	>29.49*
			Ep2	30.70±0.41	29.14±0.10	27.68±0.04	27.16±0.02	27.36±0.04	27.47±0.04	27.55±0.05	27.64±0.06
			Ec	>28.73*	29.76±0.23	27.98±0.04	27.30±0.03	27.56±0.04	27.55±0.04	27.55±0.06	27.72±0.07
			Ep3	>28.87*	29.80±0.24	28.17±0.05	27.42±0.03	27.63±0.04	27.74±0.05	27.78±0.07	27.96±0.08
SN02	64.04421	−24.07449	Ep2	28.77±0.11	27.85±0.06	27.44±0.05	27.31±0.04	27.35±0.06	27.60±0.08	27.52±0.09	27.68±0.08
			Ec	29.20±0.16	28.09±0.06	27.62±0.04	27.39±0.04	27.50±0.07	27.71±0.07	27.85±0.11	28.07±0.11
			Ep3	29.71±0.31	28.04±0.09	27.76±0.06	27.51±0.06	27.51±0.08	27.54±0.08	27.52±0.08	27.88±0.10

our search found a transient in yet another arc that no transient was seen previously (the "Mothra" arc). As mentioned above (and to be discussed in details in our forthcoming papers), these transients are most likely stars in the lensed arcs that were temporarily magnified by a higher factor due to micro lensing effect. This remains the only direct way to study individual stars at cosmological distances, and therefore should be further pursued by JWST in the coming years. An interesting discovery is that these transients could occur very frequently; this is suggested by `Dc2-W4`, a transient in the Warhol region appeared in Ec and not seen in either Ep2 (13.6 days before) or Ep3 (29.4 days after). A high cadence of ∼10 days (∼5 days in the rest frame) would potentially reveal more fast transients like `Dc2-W4`, which is worth exploring with JWST in the near future.

In addition to the 12 transients in the highly magnified arcs, we also discovered two transients within this <4 arcmin^{-2} search area in regions that are only moderately magnified ($\mu \sim$ 2–5). They are most likely SNe; given their brightness, they would also have been discovered even without the lensing magnification at the intrinsic, post-peak brightness of ∼28.5–29.0 mag. Taken at face value, these two SNe being discovered in 3.98 arcmin^2 implies that the SN surface density of ∼0.5 arcmin^{-2} integrated up to $z \approx 2.2$ when monitored over ∼126 days, which is broadly consistent with expectaions (Wang et al. 2017; Regős & Vinkó 2019). An interesting point is that both SNe were caught at near their maxima (in the rest-frame visible range) by the Ep2 observations. Note that Ep2 was separated by 83.4 days from Ep1. Due to time dilation, neither transients changed significantly in brightness from Ep2 to Ec, which was 96.7 days after Ep1. This suggests that a time cadence of ∼90 days is effective in discovering SN-like transients (integrated over all redshifts) and is highly likely to catch the events near their peaks.

Finally, we note that there could be a color-bias in the transients reported here: the vast majority of them are very red; the only exception is SN01 in Ep1, and it also transformed to a red object in Ep2. We believe that this is at least in part due to the fact that the initial selection was based on the F356W difference images. An initial selection based an SW band (e.g., F150W) is possible, although it would be more complex in the visual validation due to the more numerous defects in the SW data. We will defer such an attempt to a future paper.

5. SUMMARY

M0416 has been observed by NIRCam for four epochs, which makes it the most intensely monitored field by the JWST in its Cycle 1. The eight-band data also provide the best near-IR SED sampling to date. In this work, we present the transients identified in these four epochs that spanned over 126 days. In total, we have identified 14 transients. Twelve of them occurred in three regions highly lensed by the cluster (seven, four, and one in the Warhol, Spock, and Mothra regions, respectively), while the other two happened in two background galaxies that are only moderately magnified (by ∼2–5×). The eight-band photometry enables the construction of their SEDs from 0.9 to 4.4 μm. This is the first time that time-domain studies are given such detailed information for interpretation. The analysis of these SEDs and light curves will be presented in our forthcoming papers.

Our work here demonstrates the power of JWST in the study of the transient IR sky. It is now expected that JWST will be able to function for about twenty years, which will enable various long-term JWST monitoring programs addressing new sciences never possible before. A new era of the IR time-domain science has come.

The NIRCam data presented in this paper can be accessed via 10.17909/wmmd-ev74 after the proprietary period.

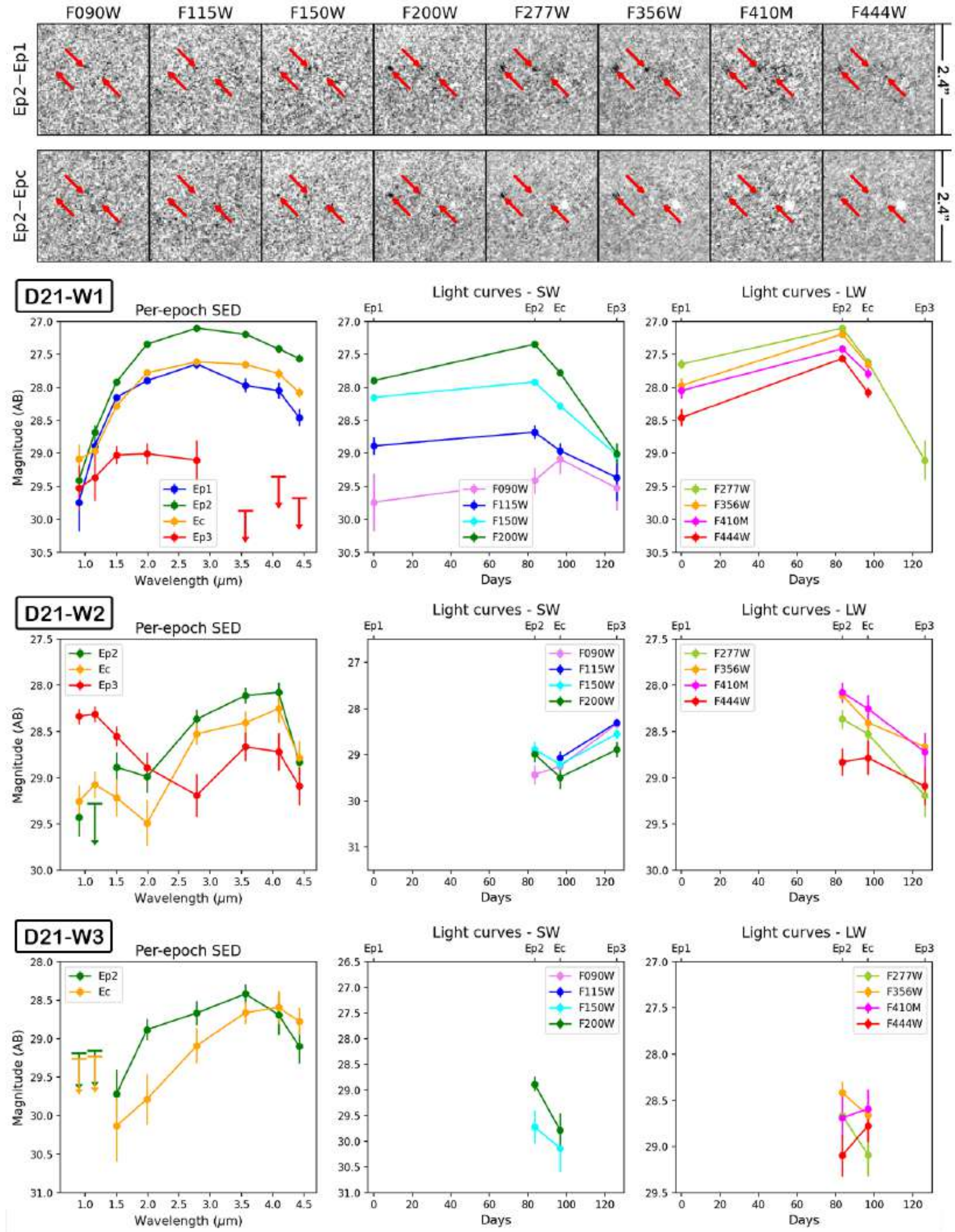

Figure 3. (top two rows) Transients D21-W1, D21-W2 and D21-W3 in the D21 (first row) and the D2c (second row) difference images in the eight NIRCam bands as labeled. The images are of the same size and orientation as in Figure 2; the red arrows mark the locations of these transients (D21-W1, D21-W2 and D21-W3 from left to right in each image). The pair of epochs forming the difference images displayed here are chosen to best capture some of the characteristics of these transients. D21-W1 (visible in all epochs) is fainter in D2c (13.3 days apart) than in D21 (83.4 days apart), suggesting that it faded rapidly after reaching its maximum in Ep2. D21-W2 (not visible in Ep1) is almost invisible in Dc2, suggesting that it decayed more slowly. D21-W3 (not visible in Ep1) was similar to D21-W2 (and is only $0''.28$ apart) but fainter. (bottom three rows) Photometric information of these three transients. From left to right in each row, these show the evolution of their SEDs, their light curves in the SW and the LW bands, respectively. Note that D21-W1 was visible in all epochs and the photometry was done in the origianl images, while the other two were not seen in Ep1 and their photometry was done on the difference images with respect to Ep1 (i.e., the D21, Dc1 and D31 images).

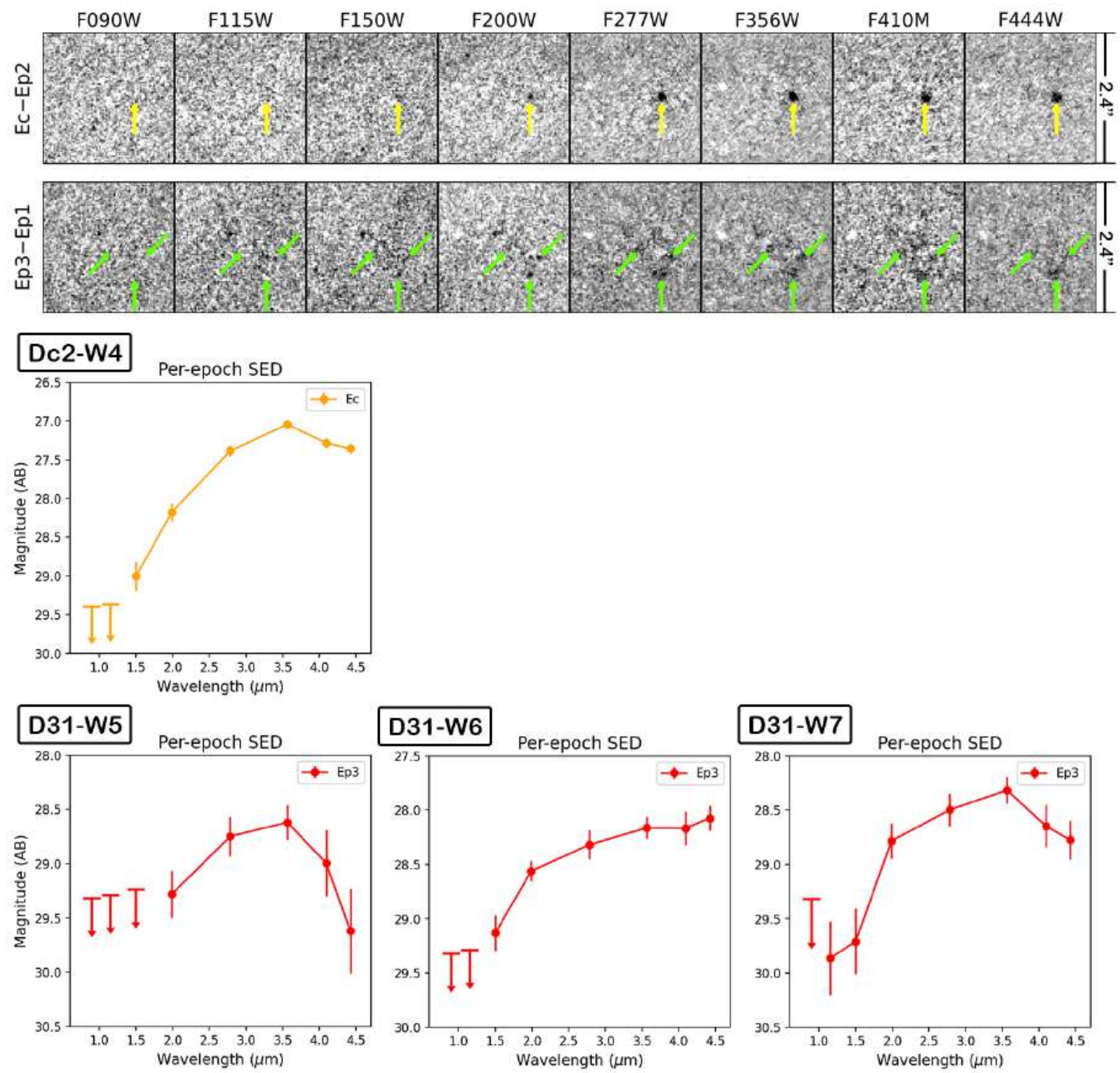

Figure 4. (top two rows) Transients Dc2-W4 in the Dc2 difference images (first row) and D31-W5, D31-W6 and D31-W7 in the D31 difference images (second row) in eight NIRCam bnads. The images are of the same size and orientation as in Figure 2. Dc2-W4 (position marked by the yellow arrow in each image) only appeared in Ec and was not visible in any other epochs, include Ep2 (only 13.3 days before Ec). D31-W5, D31-W6 and D31-W7 (positions marked by the green arrows from left to right in each image) were only visible in Ep3 and were only significant in the LW bands. (bottom two rows) SEDs of transients Dc2-W4 and D31-W5, D31-W6, and D31-W7.

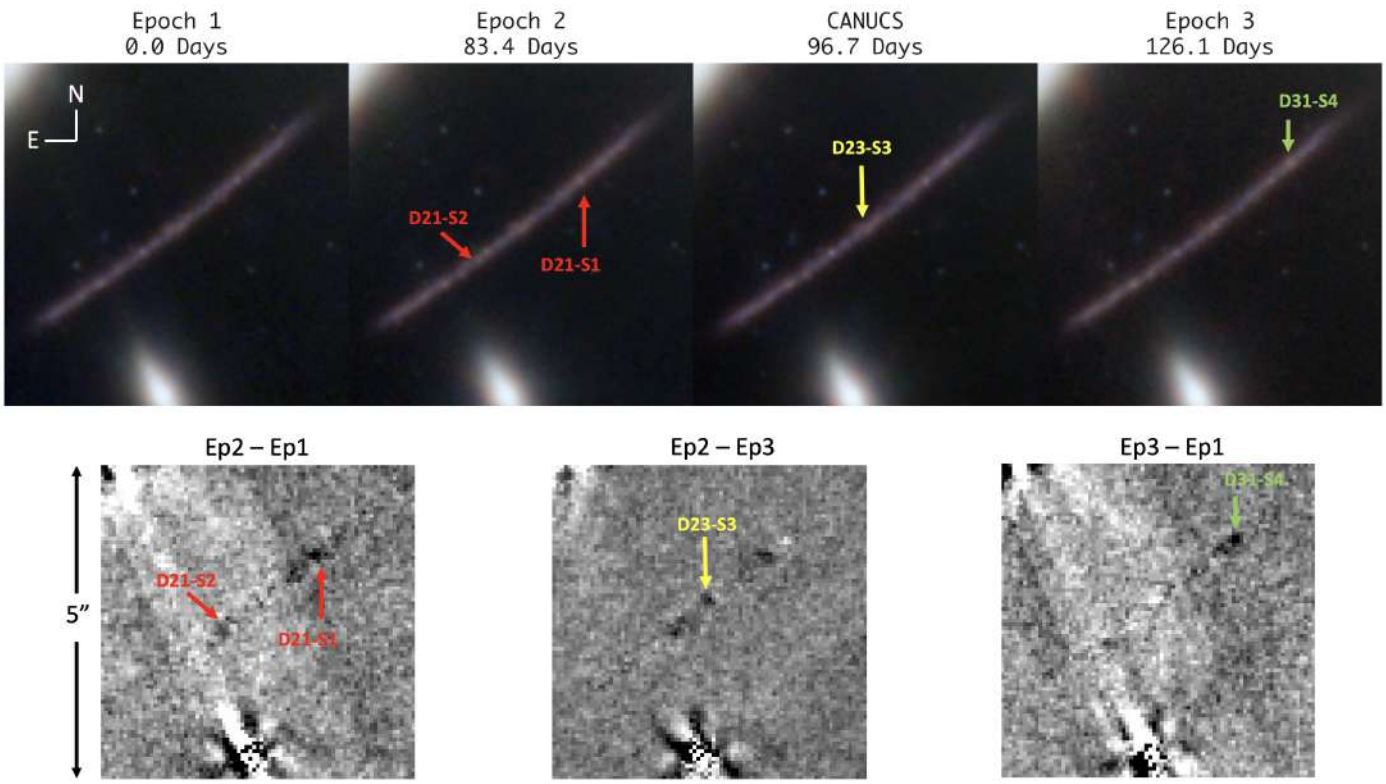

Figure 5. Similar to Figure 2, but for the transients found in the Spock region. The images are 5″ on a side.

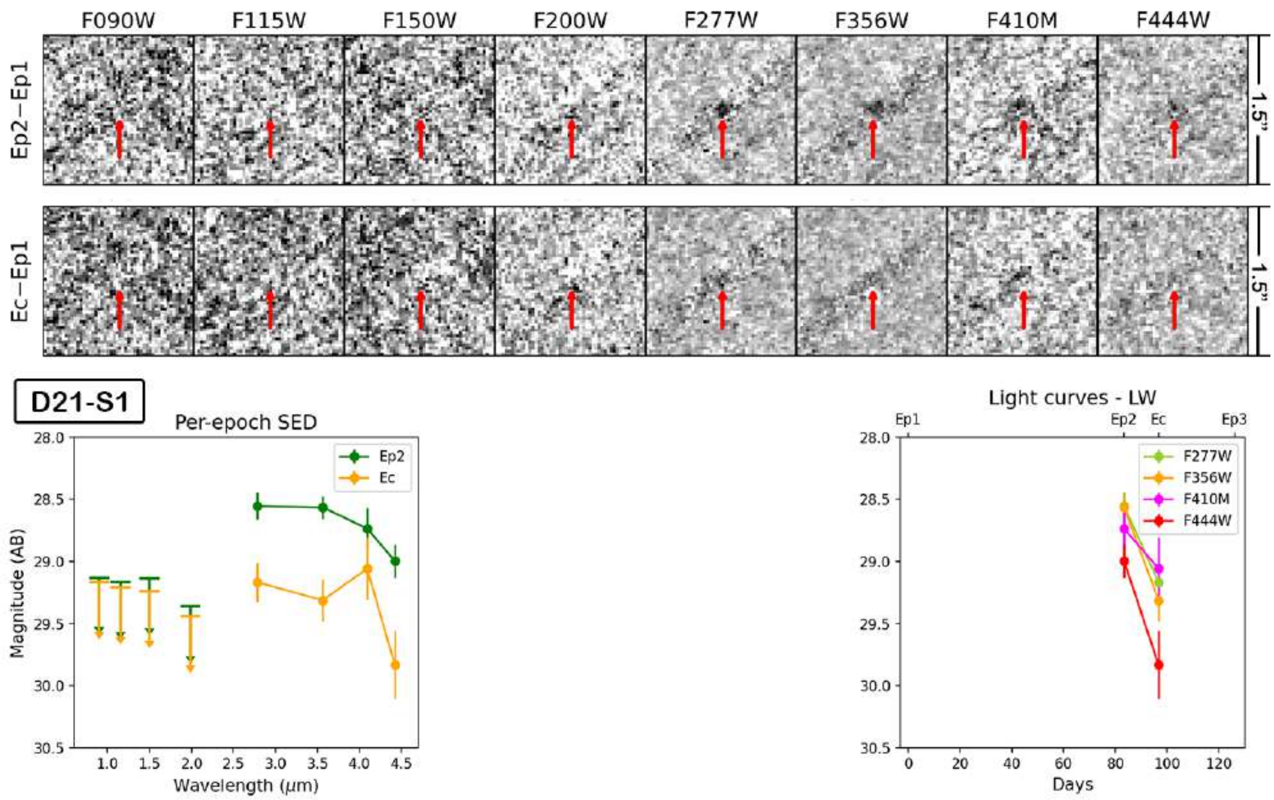

Figure 6. (top two rows) Transient D21-S1 in the D21 (first row) and Dc1 (second row) difference images. The size of the images is as noted. The transient location is marked by the red arrow in each image. It is the most prominent in the D21 images and becomes weaker in Dc1 images (but still visible), indicating that it reached the maximum in Ep2 and then rapidly declined (disappearing from Ep3 entirely). It is almost invisible in the difference images in the SW bands. (bottom row) Photometric information of this transient, similar to those presented in Figure 3 but without the light curves in SW as it was not seen in these blue bands. It is assumed that the object was not visible in Ep1, and the photometry in Ep2 and Ec is based on the D21 and Dc1 difference images.

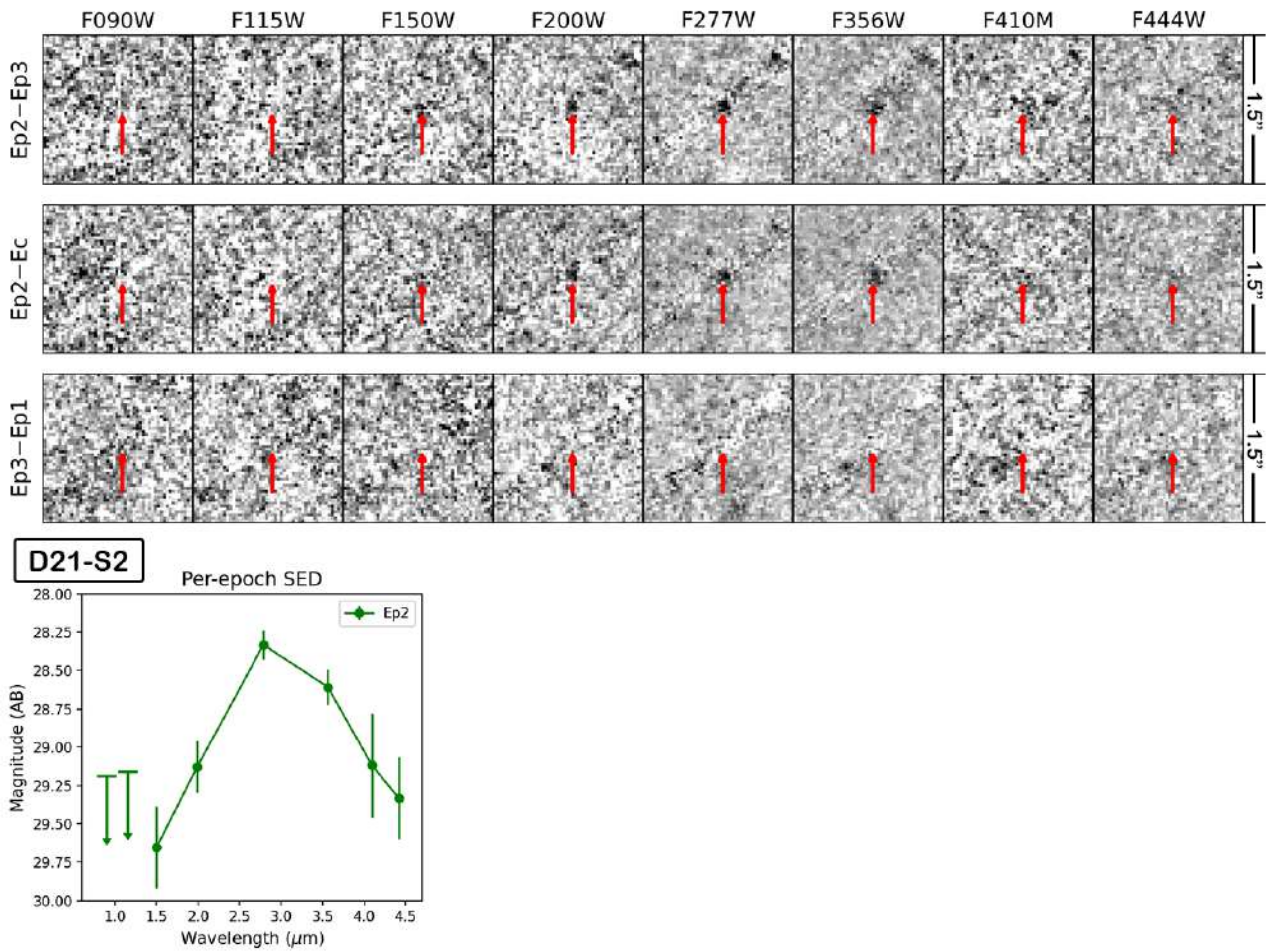

Figure 7. (top three rows) Transient D21-S2 in the D23 (first row), D2c (second row) and D31 (third row) difference images. The size of the images is as noted. The location of the transient is marked by the red arrow in each image. It is visible in the difference images involving Ep2 but not without, indicating that the event was caught only in Ep2. (bottom row) SED of the transient in Ep2 as measured from the D23 images.

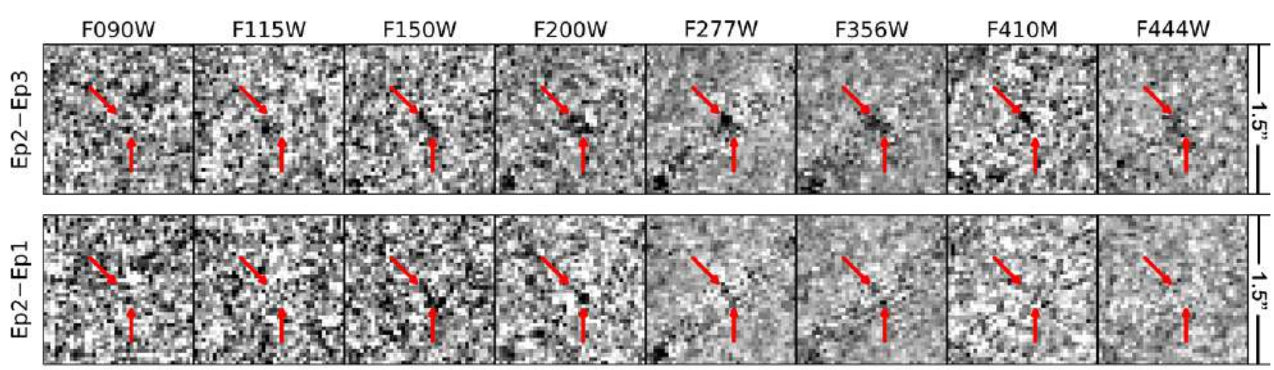

Figure 8. Transient D23-S3 in the D23 (first row) and D21 difference images. The images are of the same size as noted. The transient location is marked by the red arrow in each image. This transient, however, seems to be the most complicated among all, and the difference images of different epoch pairs reveal some inconsistencies. See text for details.

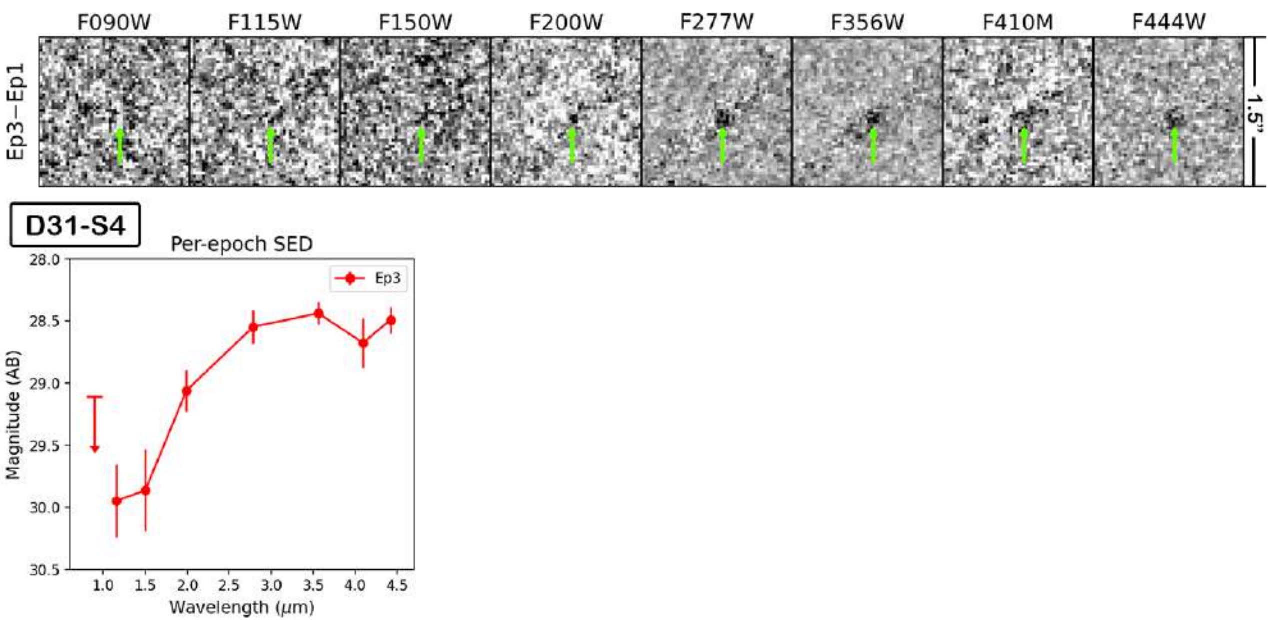

Figure 9. (top) Transient D31-S4 in the D31 difference images. The size of the images is as noted. The transient location is marked by the green arrow in each image. It is only seen in the difference images involving Ep3, indicating that it appeared in Ep3. (bottom) SED of this transient in Ep3 as measured on the D31 difference images.

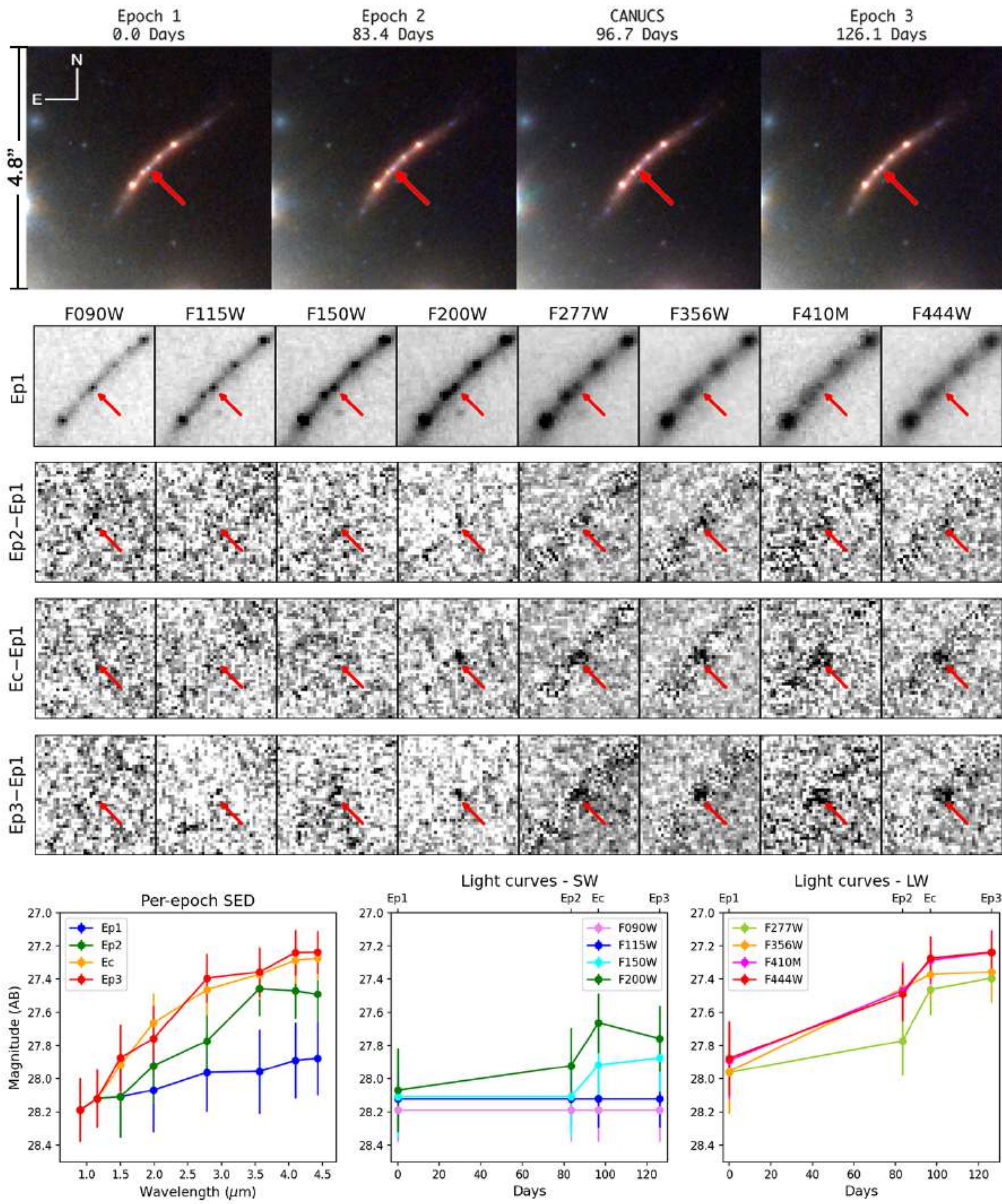

Figure 10. Transient identified in yet another arc. The top row shows the color images (4″.8 on a side) of this region in four epochs, where the red arrow in each image points to the knot that gave rise to the event. The second row zooms in to the arc and shows the Ep1 images (1″.2 on a side) in the eight bands. The next three rows show the difference images between other epochs and Ep1. The last row shows the photometric information. See Section 3.2.3 and the Appendix for the details of the photometry.

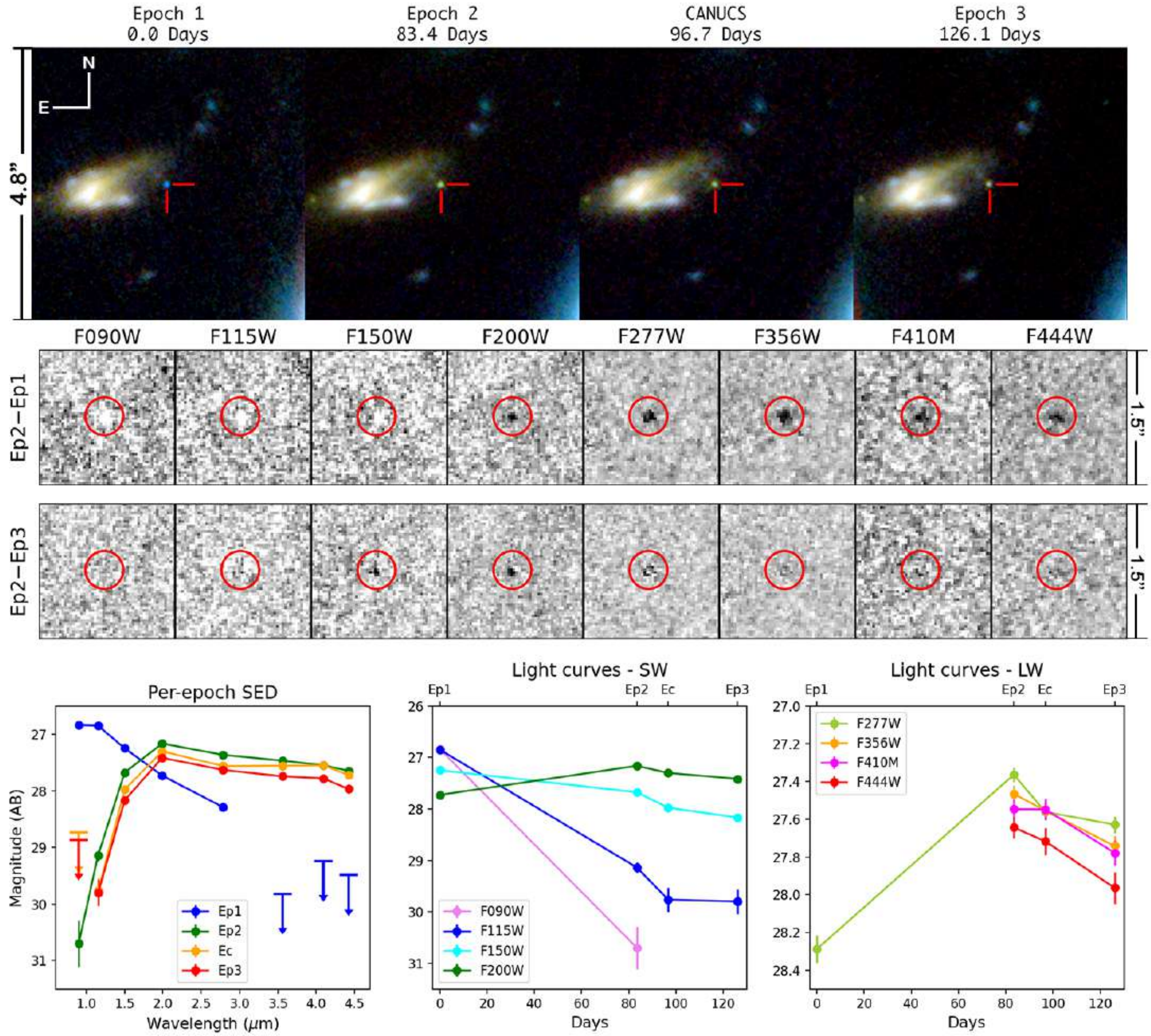

Figure 11. (top row) Color images of SN01 in four epochs, with the scale and orientation noted. The position of the SN is indicated by the red arrow in each image. The nearby irregular galaxy is presumably the host, which is at $z = 2.205$. The transient appeared as a very blue object in Ep1 and quickly changed to green/yellow color in the following epochs. (middle two rows) D21 and D23 difference images that capture some of the characteristics of this transient. The location of the source is indicated by the red circle ($0''.5$ in radius) in each image. The change of color from blue to green/yellow is obvious in the D21 images, where its location shows negative signals in the three bluest bands and positive signals in the rest. It largely maintained the same color from Ep2 through Ep3 (although becoming dimmer) as seen in the D23 images. (bottom row) SED evolution over four epochs (left panel) and the light curves in the SW bands (middle) and the LW bands (right). In Ep1, this transient was invisible in the three reddest bands, and the downward arrows in its Ep1 SED indicate the 5 σ upper limits in these bands (calculated on the error maps within $0''.165$ radius circular aperture to best match the size within which the PSF fitting was done; see the Appendix). In F200W and the redder bands, the transient reached the maximum in Ep2 and then gradually faded.

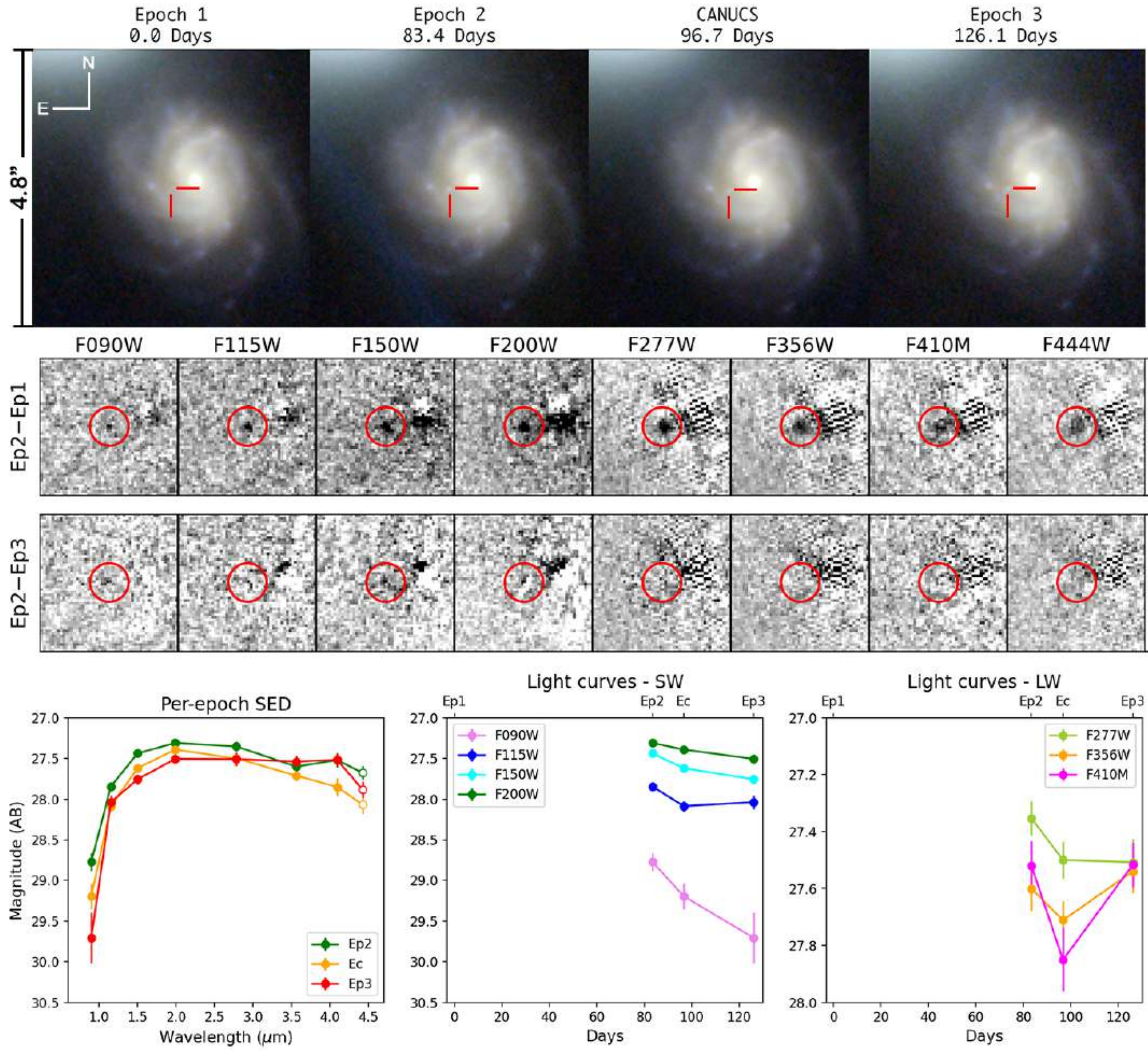

Figure 12. Similar to Figure 11, but for SN02. The two red bars in each of the color images indicate its location. It was not visible in Ep1. From the difference images involving Ep2, it seems that this transient reached the maximum in Ep2 and then faded. The host redshift is $z = 0.7093$.

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APPENDIX

While we used isophotal aperture photometry by SExtractor to search for transients, we used PSF fitting for the final photometry of the identified transients. This approach assumes that transients are all point-like even under the JWST resolution, which should be valid. The reason that we adopted the more complicated PSF fitting (as opposed to aperture photometry) was because of the background contamination. Our transients were all embedded in highly non-uniform background, and in a lot of cases it still leaves structures even in the difference images between epochs. In such situations, PSF fitting handles contamination better than any aperture photometry. We did PSF fitting on the 30mas images (as opposed to the 60mas used in the transient identification). The process is outlined as follows.

We first generated the PSFs using the simulation tool `WebbPSF` (version 1.1.1) at the pixel scale of 30mas. For each band, PSFs were simulated at 36 evenly distributed positions on each detector, and each simulated PSF was saved as an individual image. All simulated PSFs were 87×87 pixels ($2.''61\times2.''61$) in size. Then, effective PSFs are built using `EPSFBuilder` in `Photutils`. Hereafter these PSFs are referred to as the WPSFs. In the meantime, we also constructed empirical PSFs for comparison. The difficulty is that the M0416 field does not have many suitable stars. Nevertheless, we were able to find five isolated, unsaturated and high $\mathrm{S/N}$ stars for this purpose. A region of 87×87 pixels centered on each star was cut out from the image, and the five cutouts were sent to `EPSFBuilder` to build the empirical PSF. These empirical PSFs are referred to as the EPSFs henceforth. Both types of PSFs were used, and we found only marginal differences (see below).

We used `BasicPSFPhotometry` function in `Photutils` to perform PSF fitting. This function also allows simultaneous fit to multiple, overlapping sources when necessary. The non-linear fitting routine `LevMarLSQFitter` in `Astropy` is applied, which utilizes the least-square statistics to decide on the best fit. In PSF fitting, the actual area used to fit the model is usually much smaller than the full PSF size, as only the centeral region has sufficient $\mathrm{S/N}$. Here we found that the optimal fitting area was 11×11 pixels, which is about $2.8\times$ the full-width-at-half-maximum of the F356W PSF.

We provided an initial guess of the source's centroid and flux when running the fit. The former was estimated by visually locating the peak pixel, while the latter was estimated by measuring the aperture flux within a circle of 11 pixels in diameter centered at the initial guess of the location. We found that `BasicPSFPhotometry` could converge to the same solution even when the initial guesses were widely different. On the other hand, the routine requires an accurate background estimate because it fixes the background to the input value. In most cases, we estimated the background by using the `MedianBackground` function in `Photutils` and adopting the 3 σ-clipped median in the image cutouts centered on the transient (i.e., the same image stamps as shown in the figures in the main text) with the sources masked.

However, this general routine was not applicable in some special cases, for which tailored treatments were necessary. For example, leaving both the source location and its flux as free parameters was not feasible for the sources of low $\mathrm{S/N}$. In these cases, we fixed the centroid and fit for the flux. For several sources in the highly magnified regions, small but notable positional offsets were found between some SW and LW bands. In such cases, we did not force the fit to be centered at the same position; instead, we determined the centroid in different bands individually. Regarding the background estimation, median statistics were not applicable for the sources in extremely non-uniform local backgrounds. For these cases, we estimated the local background value manually in an iterative manner: we subtracted different constants from the image at a step size of 0.005 MJy/sr, performed a PSF fitting, and visually examined the residual image to determine the best local background value by eye. We note below the sources that were applied some of these special treatments.

- D21-W2   We determined the source's centroids in the LW bands using the D21 images and in the SW bands using the D31 images. Their centroids in each band were then fixed for all epochs.
- D21-W3   The source's centroids were determined from the D21 images and then fixed for Ec.
- Dc2-W4   This source's local background is non-uniform; thus, we visually examined and selected the best local background value in Ec.
- D31-W5/W6/W7   These sources' centroids in the SW bands were determined from the D31 F200W image; in the LW bands, they were determined from the D31 F356W image.
- D21-S2   This source's centroids in the SW bands were determined from the F200W D21 image; in the LW bands, they were determined from the D21 F277W image.
- D31-S4   This source's centroids in F115W and F150W were fixed to its F200W centroid.
- Mothra   (1) In Ep1, this source's centroid in F444W were fixed to its F410M centroid. (2) The complexity of simultaneously fitting two overlapping sources on a thin arc made it hard to use any automatic approach to estimate the local background. Therefore, we had to tune the background estimate manually as mentioned above. Furthermore, we used the Ep1 difference images between adjacent bands (the bluer image was always PSF-matched to the redder image when constructing the difference) to judge whether the extracted flux in each band was reasonable under each step of background estimate. For example, if the F150W-F115W difference image shows a distinct source at the transient location, it means that the extracted flux in F150W must be higher than that in F115W. This added constraint, while tedious, allowed us to further tweak the background values to obtain the most reasonable flux measurements.

In all cases, our PSF-fitting results have been properly normalized by aperture correction. As mentioned above, we used five stars to construct the EPSFs; these five stars were our basis for the aperture correction. We ran PSF fitting on these five stars to obtain their fitted fluxes, and also derived their aperture fluxes within the same 11×11 pixel areas. The averaged ratio between the two in each band was the multiplicative aperture correction factor, which we applied to the outputs from `BasicPSFPhotometry`.

Finally, we note that there are only marginal differences between the results based on the WPSFs and those based on the EPSFs. As the EPSFs were derived using only a small number of stars (total of five), we regard them as being less secure. Therefore, we adopted the WSPF results for our final photometry reported in the tables.

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