Hubble Space Telescope Imaging of Luminous Extragalactic Infrared Transients and Variables from the Spitzer Infrared Intensive Transients Survey*

Howard E. Bond1,2, Jacob E. Jencson3, Patricia A. Whitelock4,5, Scott M. Adams6,7, John Bally8, Ann Marie Cody9, Robert D. Gehrz10, Mansi M. Kasliwal10, and Frank J. Masci11

1 Department of Astronomy & Astrophysics, Pennsylvania State University, University Park, PA 16802, USA; heb11@psu.edu
2 Space Telescope Science Institute, 3700 San Martin Dr., Baltimore, MD 21218, USA
3 Steward Observatory, University of Arizona, 933 N Cherry Ave., Tucson, AZ 85721-0065, USA
4 South African Astronomical Observatory, P.O. Box 9, 7935 Observatory, South Africa
5 Department of Astronomy, University of Cape Town, Private Bag X3, Rondebosch 7701, South Africa
6 Cahill Center for Astronomy & Astrophysics, California Institute of Technology, Pasadena, CA 91125, USA
7 Present address: Orbital Insight, 1201 N Wilson Blvd., Suite 2100, Arlington, VA 22209, USA
8 Center for Astrophysics & Space Astronomy, Astrophysical & Planetary Sciences Department, University of Colorado, UCB 389, Boulder, CO 80309, USA
9 SETI Institute, 339 Bernardo Ave., Suite 200, Mountain View, CA 94043, USA
10 Minnesota Institute for Astrophysics, School of Physics & Astronomy, University of Minnesota, 116 Church St. SE, Minneapolis, MN 55455, USA
11 IPAC, California Institute of Technology, 1200 E California Blvd., Pasadena, CA 91125, USA

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Abstract

The SPitzer InfraRed Intensive Transients Survey (SPIRITS) searched for luminous infrared (IR) transients and variables in nearly 200 nearby galaxies from 2014 to 2019, using the warm Spitzer telescope at 3.6 and 4.5 μm. Among the SPIRITS variables are IR-bright objects that are undetected in ground-based optical surveys. We classify them as (1) transients, (2) periodic variables, and (3) irregular variables. The transients include eSpecially Red Intermediate-luminosity Transient Events (SPRITEs), having maximum luminosities fainter than supernovae, red IR colors, and a wide range of outburst durations (days to years). Here we report deep optical and near-IR imaging with the Hubble Space Telescope (HST) of 21 SPIRITS variables. They were initially considered SPRITE transients, but many eventually proved instead to be periodic or irregular variables as more data were collected. HST images show most of these cool and dusty variables are associated with star-forming regions in late-type galaxies, implying an origin in massive stars. Two SPRITEs lacked optical progenitors in deep preoutburst HST images; however, one was detected during eruption at J and H, indicating a dusty object with an effective temperature of ∼1050 K. One faint SPRITE turned out to be a dusty classical nova. About half the HST targets proved to be periodic variables, with pulsation periods of 670–2160 days; they are likely dusty asymptotic-giant-branch (AGB) stars with masses of ∼5–10 M☉. A few of them were warm enough to be detected in deep HST frames, but most are too cool. Out of six irregular variables, two were red supergiants with optical counterparts in HST images; four were too enshrouded for HST detection.

Unified Astronomy Thesaurus concepts: Supernovae (1668); Transient sources (1851); Classical novae (251); Variable stars (1761); Infrared sources (793); OH/IR stars (1156); Red supergiant stars (1375); Luminous blue variable stars (944)

Supporting material: data behind figure

1. SPIRITS: Searching for Extragalactic Infrared Transients and Variables

Several classes of luminous variable stars and optical transients (OTs) have been known for many decades—most famously supernovae (SNe), classical novae (CNe), and luminous blue variables (LBVs). In recent years, wide-field optical imaging surveys have been finding OTs in increasingly large numbers, and the discovery rates are now becoming enormous. However, optical surveys are relatively insensitive to objects that are intrinsically cool, dusty, or located in obscured regions. Thus our knowledge of variable and transient phenomena occurring primarily at infrared (IR) wavelengths has, until fairly recently, been limited.

In 2014, our team started a systematic search for luminous IR transients and variables in nearby galaxies, called the Spitzer InfraRed Intensive Transients Survey (SPIRITS). Our survey used the Infrared Array Camera (IRAC; Fazio et al. 2004) on the warm Spitzer Space Telescope to search for variable extragalactic objects at wavelengths of 3.6 and 4.5 μm. From 2014 to 2016, our target list contained ∼190 galaxies, consisting of about 37 galaxies within 5 Mpc, 116 luminous galaxies with distances of about 5–15 Mpc, and the 37 most luminous galaxies in the Virgo cluster at 17 Mpc. From 2017 through the end of the survey in 2019 December, we reduced our target list to a subset of the 105 galaxies of the original sample most likely to host new transients, including the most luminous and actively star-forming galaxies, and the 58 galaxies that had previously hosted an IR transient candidate. Observing cadences ranged from a few weeks to several years,
augmented with additional data available in the Spitzer archive.\textsuperscript{12} The nominal S/N = 5 limiting magnitudes for isolated objects in our exposures are [3.6] = 20.0 and [4.5] = 19.1 (Vega scale). These correspond to absolute magnitudes of $\sim$8.5 and $\sim$9.4 at 5 Mpc, and $\sim$10.9 and $\sim$11.8 at 15 Mpc. However, in practice the limiting magnitudes are affected by our ability to remove the background in image subtraction, and the detection limits can be substantially brighter than the nominal values.

Details of the SPIRITS image-processing and variable-identification pipeline are given in Kasliwal et al. (2017, hereafter K17). The pipeline includes subtraction of template reference images, for which we used available archival frames, the Post-basic Calibrated Data–level mosaics, including Super Mosaics,\textsuperscript{13} or images from the Spitzer Survey of Stellar Structure in Galaxies (S4G; PID 61065, PI K. Sheth). Where Super Mosaics or S4G mosaics were not available, we used stacks of archival BCD-level images. For all “saved” sources, those vetted by human scanners and given a SPIRITS designation, we performed aperture photometry on the difference images using a 4 mosaicked-pixel (2”4) aperture and background annulus from 4–12 pixels (2”4–7”2). The extracted flux is multiplied by aperture corrections of 1.215 for [3.6] and 1.233 for [4.5], as described in the IRAC Instrument Handbook,\textsuperscript{14} and converted to Vega-system magnitudes using the Handbook-defined zero-magnitude fluxes for both IRAC channels. The final photometry that we employ places a grid of apertures near each individual source position to robustly estimate the uncertainties and upper limits, as described in Jencson (2020, hereafter J20). For nontransient, variable sources (where the difference flux measured may be negative; see our definitions below in Section 2), if there is a plausible, identifiable counterpart source in the reference images, we add the flux of the source from aperture photometry on the reference images to our difference photometry. Otherwise, we offset the difference-flux measurements of a given light curve to bring the minimum, negative value to zero before converting to magnitudes. All photometry presented in this work is provided as the data behind the figures. Full details of the SPIRITS survey and initial discoveries are presented in K17, and updated overviews are given by Jencson et al. (2019) and J20.

2. SPIRITS Variables and SPRITEs

Based on what was known about OTs at the beginning of the SPIRITS survey, we anticipated at a minimum that we would discover members of known classes of dusty transients, as well as heavily optically obscured SNe. The category of dusty OTs includes eruptive events with peak luminosities between those of SNe and CNes, which appear to fall into two main groups:

(1) “Intermediate-luminosity red transients” (ILRTs), typified by NGC 300 OT2008-1 (Bond et al. 2009) and SN 2008S in NGC 6946 (Szczerygiel et al. 2012). The progenitors of both of these events were detected in archival Spitzer images as luminous mid-IR sources (Prieto 2008; Prieto et al. 2008), which were heavily obscured at optical wavelengths. The outflows from ILRTs form substantial dust, and they are bright IR sources at late times after their optical light has faded (e.g., Kochanek 2011, and references therein). ILRTs are strongly associated with spiral arms, indicating that they arise from fairly massive stars. The origin of ILRT outbursts is debated: proposed mechanisms include electron-capture SNe, low-mass core-collapse SNe, events related to LBV eruptions, and binary interactions (see discussion and references in Adams et al. 2016; Cai et al. 2018, 2019, 2021). A recently discovered likely member of this class, M51 OT2019-1 (AT 2019abn), had a massive, self-obscured progenitor similar to the two class prototypes, and it was shown to be variable in the 12 years of available preoutburst archival imaging with Spitzer/IRAC (Jencson et al. 2019). An extended phase of early circumstellar dust destruction observed during the rise of this transient disfavors a terminal-explosion scenario, strengthening the connection between ILRTs and giant eruptions of LBVs (Jencson et al. 2019; Williams et al. 2020).

(2) “Luminous red nova” (LRNe), a lower-luminosity class of dust-forming transients, generally (but not always) associated with older populations. Examples include M31 RV and V4332 Sgr (Bond 2011, 2018, and references therein) and V838 Mon (Sparks et al. 2008; Woodward et al. 2021). These events are probably the result of common-envelope interactions and stellar mergers (e.g., Pastorello et al. 2019; Howitt et al. 2020); this was definitely the case for the LRN V1309 Sco, which was shown to have been a close binary with a rapidly decreasing orbital period before its eruption (Tylenda et al. 2011).

As reported by K17, our initial analysis of the SPIRITS data indeed revealed numerous IR transients and variables. An unexpected finding was a new class of IR transients that lack counterparts in deep optical imaging during outburst—unlike the ILRTs and LRNe described above—and have maximum IR luminosities lying between those of CNes and SNe. We refer to these objects as eSpecially Red Intermediate-luminosity Transient Events (SPRITEs). These events were defined in K17 as transients with absolute magnitudes at maximum in the range $-14 < M_{[4.5]} < -11$, IR colors in the range $0.3 < [3.6]−[4.5] < 1.6$, and having no optical counterparts detected during the outbursts in deep ground-based images.

A second surprise emerged as the SPIRITS program continued to collect data. Several luminous stars initially considered to be transients based on a small number of observations showing a rising brightness, including several of the candidate SPRITEs, were found to be periodic variables when more Spitzer data became available. In fact, it is striking how many luminous variable stars are conspicuous in late-type galaxies, when Spitzer frames taken over several years are blinked. The contrast with what is seen at optical wavelengths, where bright variables are rare, is remarkable. These objects are most likely pulsating cool and dusty stars, with very long periods, up to several years. Most of them are probably dust-obscured AGB stars, similar to, but more luminous than, those found in the Large Magellanic Cloud and other nearby galaxies, as described by Whitelock et al. (2003), Goldman et al. (2017), Whitelock et al. (2018), and Menzies et al. (2019). They may be analogs of the OH/IR stars found close to the plane in our own Galaxy (e.g., Epchtein & Nguyen-Quang-Rieu 1982; Jones et al. 1982).

These IR-luminous pulsators have been discussed by (Karambelkar et al. 2019, hereafter K19), who present a catalog of over 400 periodic or suspected periodic variables.
found in the SPIRITS survey. Another recent study of pulsating IR variables, based in part on SPIRITS data for galaxies in the Local Group, has been presented by Goldman et al. (2019). However, we cannot rule out that some of these apparently periodic objects may actually be massive binaries with very long orbital periods, rather than pulsators. For example, Williams et al. (2012) have described a binary system containing a carbon-rich Wolf–Rayet (WC) star, which periodically forms dust during periastron passage when its wind collides with the outflow from a companion star. Recently, we reported six extragalactic WC binary candidates displaying such dust formation episodes as mid-IR SPIRITS variables, including the mid-IR counterpart to the recently discovered colliding-wind WC4+O binary candidate, N604-WRXc, in M33 (Lau et al. 2021).

A few of the SPIRITS transients are so luminous that they are very likely to be obscured SNe (Jencson et al. 2017, 2019). In a few cases these objects did prove to have detectable optical counterparts. An example is SPIRITS 16tn in NGC 3556, at a distance of only 8.8 Mpc, which reached at least $M_{(B, J)} = -16.7$ (Jencson et al. 2018). It had been missed in optical SN surveys, but following the SPIRITS discovery it was detected in deep Hubble Space Telescope (HST) and ground-based images at $I$ and $JHK$. Its optical extinction is estimated to be $A_V \approx 8–9$. This event raises the possibility that some of the SPIRITS transients with relatively few observations could have been obscured SNe that happened not to be imaged around their times of maximum light.

Young stellar objects (YSOs) are another potential source of transient phenomena at IR wavelengths. Some low- to moderate-mass YSOs experience sudden $\sim 5–10$ magnitude increases at visual wavelengths, followed by a gradual decline lasting years to decades. These “FU Orionis” outbursts are thought to be triggered by enhanced accretion from a circumstellar disk onto the YSO (e.g., Hartmann & Kenyon 1996). The Spitzer YOS Variability project (Rebull et al. 2014) found that most YSOs are variable in the IR, and some experience luminous outbursts. In 2015, two massive YSOs underwent $\sim 4 \times 10^{5} L_\odot$ IR flares (Hunter et al. 2017; Caratti o Garatti et al. 2017). More luminous events are thought to be associated with explosions such as the $\sim 550$ yr-old BN/KL outflow in Orion OMC1 (Bally et al. 2020). Bally & Zinnecker (2005) proposed that mergers of the most massive stars can produce IR flares with luminosities comparable to those of SNe. Numerical simulations show that, in dense cloud cores, orbital decay can induce massive stars and binaries to migrate rapidly to the core’s center to form nonhierarchical systems. Such systems are unstable. $N$-body interactions tend to rearrange them into hierarchical configurations, compact binaries, and ejected stars (e.g., Reipurth & Mikkola 2015). In sufficiently dense subgroups, $N$-body interactions may lead to YSO mergers. In a molecular cloud, dust shifts the UV and visual light from major accretion events and stellar mergers into the IR or submillimeter. The resulting luminous IR flares are expected to be similar to some SPIRITS IR transients.

### 3. HST Follow-up of SPIRITS Variables

In the present paper we report results of follow-up optical and near-IR imaging observations of SPRITEs and other SPIRITS transients and variables, made with HST and its Wide Field Camera 3 (WFC3). We received allocations of two HST orbits for an initial Director’s Discretionary program in Cycle 21 (GO/DD-13935, PI H.E.B.), and eight orbits for a regular Cycle 23 program (GO-14258, PI H.E.B.). Two observing programs from another team (GO-14463 in Cycle 23, GO-14892 in Cycle 24, both with PI B. McCollum) were devoted to imaging of two further SPIRITS transients; we have obtained these data from the public HST archive and include analyses of them in this paper. In addition to our newly obtained WFC3 images from these programs, we downloaded HST frames of the sites from the archive; these had been secured with the Wide-field Planetary Camera 2 (WFPC2) and the Advanced Camera for Surveys (ACS), as well as WFC3.

The main goals of our HST imaging were: (1) deep searches for optical/near-IR counterparts of SPRITEs while the events were underway; (2) characterization of their stellar environments; and (3) identification of (or limits on) progenitor objects by comparison of our new HST images with preoutburst archival images.

Our primary considerations for HST target selection were: (1) the outburst event appeared to satisfy the photometric criteria for SPRITEs outlined above, and was expected to be underway during the HST observation; (2) there was no detected optical counterpart in concomitant optical ground-based imaging with moderate-aperture telescopes (to rule out ordinary CNe, SNe, LBVs, and other known types of OTs); and (3) the site of the SPRITE had been imaged previously by HST at the F814W band (or longward in a few cases). As noted by K17, SPRITEs appear to have a wide duration of outburst timescales, ranging from fast events to long-duration eruptions. We attempted to sample transients spanning this range.

Table 1 lists the SPIRITS targets that were observed in the four HST programs. Columns 1 and 2 list the object designations and host galaxies, and column 3 gives the date of the HST observation. Column 4 contains the HST program ID number. Our WFC3 observations were made in the UVIS-channel F814W bandpass, and the IR-channel F110W and F160W filters (although in one case we omitted the F110W image). Hereafter in this paper we denote these filters as $I$, $J$, and $H$, respectively, but we emphasize that these should not be confused with the ground-based bandpasses with the same designations.

For most of the observations we used small subarrays, rather than read out the entire detector, in order to obtain more exposure time during the HST visits. In four cases, we adjusted the HST pointing, and used a larger subarray, so as to include one or two additional interesting SPIRITS variables in the WFC3 field of view (FOV), as indicated by the multiple entries in column 1. All exposures were taken at three dither positions, and we downloaded the default pipeline drizzle-combined images from the HST archive. Columns 5 through 7 in Table 1 list the total exposure times in each filter, which varied slightly due to HST visibility constraints. For nominal exposure times of 1500, 600, and 300 s, the limiting $(S/N = 5)$ HST Vega-scale $I, J, H$ magnitudes are 26.2, 25.2, and 23.4, respectively, based on the WFC3 exposure-time calculators (ETCs). 

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15 http://archive.stsci.edu/

16 Our observations were “nondisruptive targets of opportunity,” meaning that the HST observations were to be obtained no less than three weeks after activation. As discussed below, in a few cases of fast transients, the IR outbursts had already ended by the time of the HST observation.

17 http://etc.stsci.edu/etc/input/wfc3uvis/imaging; the listed values are optimistic and only approximate because they neglect possible background light from the host galaxy and confusion in crowded star fields.
Our final observation in GO-14258 was actually made on the obscured SN SPIRITS 16tn, rather than a candidate SPRITE. As noted above, this target is discussed in detail by Jencson et al. (2018), and interpreted as a heavily obscured core-collapse SN. Tabulated here for completeness, but not discussed in this paper.

4. IR Light-curve Classification

Table 2 lists information on the SPIRITS variables targeted in the HST observations discussed in this paper. For each HST pointing in the table, a header gives the host galaxy and its distance modulus, from the literature sources cited in a footnote. Column 1 gives the SPIRITS designations, and columns 2 and 3 the J2000 coordinates. The final column gives our classification of each object's light curve, as described in this section.

At the time the prime targets in each field were selected for HST imaging, they were all candidate SPRITE transients. However, with the accumulation of substantial additional Spitzer data since the dates of the HST observations, we are able to refine our variability information beyond what was available at the time of selection. In particular (see Section 2), it became apparent that many of the candidate SPRITEs are actually not transients, but pulsators with very long periods—likely mass-losing intermediate-mass stars approaching the end of their AGB evolution. For the purposes of this paper, we have used the following classification scheme for transients, periodic variables, and irregular variables:

1. **Transients and SPRITEs.** These are sources that were undetected, brightened once, and then declined below detectability, and for which there are sufficient data before and/or after the outburst to rule out the categories below. Specifically, we use the criteria outlined in Section 1.3 of J20 to select bona fide transients. Transients falling within the absolute magnitude

2. **Periodic Variables.** These are objects that are variable on time scales short enough to be followed with our cameras. The periods are such that the variability is within the field of view of our cameras at the time of selection. In particular, with our filters and exposure times, the period must be short enough to ensure that the object is not missed by the next observation.

3. **Irregular Variables.** These are objects that are variable on time scales long enough to be missed with our cameras at the time of selection. For example, objects that are variable on time scales of years or decades are not considered to be irregular variables.

Notes.

* SPIRITS 16tn has been analyzed in detail by Jencson et al. (2018), and interpreted as a heavily obscured core-collapse SN. Tabulated here for completeness, but not discussed in this paper.

** Table 1 **

| SPIRITS Designations | Host Galaxy | Observation Date | Program ID | Total Exposure Time [s] | Other SPIRITS Variables in HST Field |
|---------------------|-------------|-----------------|------------|-------------------------|-------------------------------------|
| 14aje               | M101        | 2014-09-22      | 13935      | 1575 738 177            |                                     |
| 14axa               | M81         | 2014-09-26      | 13935      | 1659 671 155            |                                     |
| 14qb                | NGC 4605    | 2016-01-18      | 14258      | 584 976 14463           | 14akj, 14atl                        |
| 15mr, 15mt           | NGC 4613    | 2016-02-11      | 14258      | 1500 553 317            |                                     |
| 16aj                | NGC 2903    | 2016-04-18      | 14258      | 1290 484 137            | 14th, 17fe                         |
| 15afp               | NGC 6946    | 2016-03-19      | 14258      | 1425 738 177            |                                     |
| 15ahg, 14al, 14dd    | NGC 7793    | 2016-05-23      | 14258      | 1290 484 137            | 15ahp                              |
| 14al                | M83         | 2016-01-18      | 14258      | 1500 553 317            |                                     |
| 15nz                | M83         | 2016-02-11      | 14258      | 1500 553 317            | 15ahp                              |
| 14qb                | M83         | 2016-04-18      | 14258      | 1500 553 317            | 15ahp                              |
| 15nz, 15mt           | M83         | 2016-05-23      | 14258      | 1425 738 177            |                                     |
| 16aj                | M83         | 2016-05-23      | 14258      | 1425 738 177            |                                     |
| 15nz                | M83         | 2016-06-14      | 14258      | 1425 738 177            |                                     |
| 16na                | NGC 4214    | 2017-05-17      | 14892      | 2385 2385 2385          |                                     |

Notes:

* PI for 13935 and 14258 was H.E.B. PI for programs 14463 and 14892 was B. McCollum. In the 14463 program there were also exposures in F625W, F606W, and F140W; in 14892 there were also exposures in F105W. 

** Table 2 **

| SPIRITS Designation | R.A. (J2000) | Decl. (J2000) | Light-curve Classification |
|---------------------|--------------|--------------|-----------------------------|
| 14aje               | 14:02:55.51  | +54:23:18.5  | SPRITE (fast)               |
| 14axa               | 09:56:01.52  | +69:03:12.4  | Transient                   |
| 14afp               | 12:41:57.50  | +32:32:06.7  | Irregular                   |
| 14aj                | 13:37:03.9   | -29:50:19.7  | Periodic                    |
| 15nz                | 13:37:07.9   | -29:50:41.3  | Irregular                   |
| 15qo                | 03:18:15.2   | -66:30:30.4  | Periodic                    |
| 15azz               | 03:18:23.6   | -66:30:24.2  | Periodic                    |
| 15ahg               | 07:36:23.7   | +65:38:02.6  | Periodic                    |
| 14aj                | 07:36:32.8   | +65:37:26.1  | Periodic                    |
| 15ahp               | 07:36:30.8   | +65:37:57.8  | Periodic                    |
| 15afp               | 07:36:35.6   | +63:37:47.2  | Irregular                   |
| 14aj                | 20:34:59.6   | +40:11:18.1  | Periodic                    |
| 15qo                | 23:57:43.3   | -32:35:03.1  | Periodic                    |
| 14q                | 23:57:46.3   | -32:34:43.1  | Irregular                   |
| 14aj                | 23:57:46.2   | -32:35:20.6  | Periodic                    |
| 17fe                | 23:57:44.7   | -32:34:58.4  | SPRITE (slow)               |
| 15aj                | 09:32:11.6   | +23:30:0.0   | Irregular                   |
| 15mr                | 12:39:54.8   | +61:36:46.3  | Periodic                    |
| 15nt                | 12:40:06.9   | +61:36:22.3  | Periodic                    |
| 16ea                | 12:15:38.6   | +36:19:46.9  | Periodic                    |

Notes:

* The distance moduli adopted for the host galaxies are from these sources: M101, Jang & Lee (2017); NGC 6946, Pejcha & Prieto (2015); NGC 2903, Tully et al. (2016); all others, Tully et al. (2013).

b Probably a classical nova; see Section 6.3.
and color ranges given in Section 2, which were not detected from the ground at optical wavelengths, are called SPRITEs. We subdivide them into “fast” SPRITEs (having outburst durations of less than one typical Spitzer visibility window of $\lesssim 6$ months) and “slow” SPRITEs (having outburst durations extending over more than one visibility window).

(2) Periodic and likely periodic variables. As discussed above, K19 identified a set of SPIRITS variables with sufficient data to show that they were varying periodically, most likely due to long-period pulsations. We call the targets in the present study “periodic variables” if we have seen at least one and a half cycles of variation. If there is less time coverage, but the available light-curve shape is similar to those of the known periodic variables, we call the object “periodic?”.

(3) Irregular variables. These objects vary irregularly, in a fashion inconsistent with either of the above classes. Specifically, they do not show obvious periodicity, nor an outbursting transient behavior as described above.

5. Astrometric Registration

In order to search for optical counterparts of SPIRITS variables and transients in HST images, it is necessary to carry out a precise astrometric registration of the Spitzer and HST frames. This task is complicated by the fact that a large fraction of stars and background galaxies that are prominent at 3.6 and 4.5 $\mu$m are faint or invisible at optical wavelengths—and vice versa. In addition, sources that are isolated at HST resolution (the WFC3 plate scales are 0$''$0396 and 0$''$128 pixel$^{-1}$ in the UVIS and IR channels, respectively) are often blended at the Spitzer IRAC resolution (0$''$6 pixel$^{-1}$). These considerations make it necessary to blink the IRAC and WFC3 frames visually in order to select a sample of isolated objects common to both images—many of which are either foreground stars or compact, IR-luminous background galaxies.

In many cases, the SPIRITS variables were seen to lie in crowded locations in their host galaxies, including clusters, associations, and H II regions. In these instances, we first subtracted a reference Spitzer image, in which the variable was faint or absent, from a frame showing the variable in a bright phase. We then used these “difference” images to determine the positions of the variables in the same astrometric framework as the reference objects in the direct frames.

We employed standard tasks in IRAF and Space Telescope Science Data Analysis System (STSDAS)\(^{18}\) to determine centroid locations for the reference stars and galaxies in the frames. Then we used the \texttt{geomap} task to map the coordinate system of the Spitzer frame to the HST image, followed by the \texttt{geoxytran} task to determine the $(x,y)$ position of the Spitzer variable in the HST frame. The precision of the registrations varied depending on the number and quality of the reference objects, but generally ranged from an rms of about 0.1 to 0.3 Spitzer/IRAC pixels (0$''$06–0$''$18), or about 1.5–4.5 WFC3/UVIS pixels in the $x$ and $y$ directions. Depending on the quality of the target’s image in the Spitzer frames, the uncertainty of its position could be somewhat larger than for the reference-frame stars.

6. Infrared Transients and SPRITEs

With the accumulation of Spitzer observations and other information, only three of our targets chosen for HST follow-up have remained classified as transients. We discuss them in this section. Their IR light curves are shown in the three panels of Figure 1. In this figure, and in subsequent light-curve plots in this paper, the epochs of HST observations are marked with vertical black or gray arrows, marking the dates of our triggered observation or of the archival observations, respectively. As our targets are faint and extremely red, we generally only consider archival HST images taken in broad-band filters at $I$ (F814W) or longer wavelengths.

For the transients and SPRITEs, we also include optical constraints from wide-field, untargeted surveys, namely, the intermediate Palomar Transient Factory (iPTF; Cao et al. 2016) and the ATLAS (Tonry et al. 2018; Smith et al. 2020). The iPTF constraints, originally reported in Appendix 2 of J20, consist of forced-photometry measurements on the g- and Mould R-band difference images at the locations of our transients using the Palomar Transient Factory IPAC/iPTF Discovery Engine (PTFIDE) tool (Masci et al. 2017), stacked in 10 day windows to provide deeper limits. ATLAS constraints were obtained from forced photometry\(^{19}\) on the available ATLAS-c (“cyan”) and ATLAS-o (“orange”) difference images, again stacked in 10 day windows.

Table 3 summarizes several properties of the light curves of the three transients, including information on the dates they were detectable, dates of maximum light, their apparent and absolute magnitudes at peak, and the [3.6] – [4.5] color at peak.

6.1. 14aje: Fast SPRITE

The Spitzer light curves of SPRITEs 14aje in M101 ($d \approx 6.8$ Mpc) are shown in the left-hand panel of Figure 1. This transient was first detected on 2014 March 26, at an apparent magnitude of $[4.5] = 15.52 \pm 0.03$. This corresponds to an absolute magnitude of $M_{4.5} \approx -13.6$ at the distance of M101, well above the brightest IR luminosities observed for CNe (see Section 6.3). Its color was extremely red, $[4.5] - [3.6] = 1.73$. The transient had been undetected in an archival Spitzer observation at 4.5 $\mu$m in 2012 and is not present in available Super Mosaic images (2004–2007 stack; see below for more details). 14aje faded quickly, dropping by $\sim 0.6$ mag on 2014 April 24. It was below detection at our next visit on 2014 September 2, and at all of our Spitzer observations since then. As presented in Appendix 2 of J20, limits from iPTF constrain any transient optical emission during the IR outburst to $r \gtrsim 21$ mag. We classify 14aje as a fast SPRITE, confirming the initial classification by K17.

We triggered our first HST SPIRITS follow-up observations on this transient, obtaining WFC3 frames on 2014 September 22. In addition to our HST data, there was subsequent archival imaging in an unrelated program in 2017 (GO-14678, PI B. Shappee); both dates are marked with arrows in the light-curve figure. An earlier archival observation was obtained in 2003 (GO-9492, PI F. Bresolin), outside the plotted time interval. Our HST observations were discussed briefly by K17, but are updated here.

\(^{18}\) The IRAF was distributed by the National Optical Astronomy Observatory, which was operated by the Association of Universities for Research in Astronomy (AURA) under a cooperative agreement with the National Science Foundation. The STSDAS was distributed by the Space Telescope Science Institute, which is operated by AURA for NASA.

\(^{19}\) ATLAS forced-photometry server: https://fallingstar-data.com/forcedphot/.
As the light curve shows, the 14aje event was so fast that the IR outburst unfortunately appears to have ended at an uncertain date before the epoch of our triggered HST observations. We registered Spitzer frames showing 14aje at maximum with the HST ACS images taken in 2003 and 2017, in order to determine its location in the HST frames. (We chose the ACS frames because of their large FOVs, providing more astrometric reference sources than our own WFC3 images obtained with smaller subarrays.) The top panel in Figure 2 shows a color rendition of the SPRITE’s environment, taken from the Hubble Legacy Archive (HLA). The site lies in a spiral arm of M101, with several young associations nearby containing blue supergiants and a few red supergiants. The transient is located in a dark dust lane, but does not appear to lie within a rich association. The bottom three panels in Figure 2 zoom in on the site in the WFC3 images we obtained several months after the outburst in, from left to right, I, J, and H. The green circles show the 3σ error locations from the astrometric registration. There are several faint stars within the error circle in the I frame, the brightest of which is more conspicuous in the J and H images. The apparent magnitudes (Vega scale) of this star are $I = 25.8$, $J = 23.3$, and $H = 22.2$, according to photometry from the Hubble Source Catalog (HSC). The HLA display of the field. However, none of the stars within the error circle varied significantly in the I-band frames taken in 2003, 2014, and 2017. Thus we conclude that we did not detect the transient with HST a few months after its IR eruption had ended. Moreover, aside from the possibility that the object was able to return to essentially the same quiescent level it had before outburst, we have no compelling identification of an optical progenitor. These observations, along with the rapidity of the IR transient, make this SPRITE event qualitatively different from ILRTs like NGC 300 OT2008-1, SN 2008S, and M51 OT2019-1, which would have been detected easily by HST a few months after their outbursts at I, J, and H.

There is also no pre-eruption IR counterpart detected in the available archival Spitzer/IRAC imaging. We examined the location of the event in the Spitzer Heritage Archive Super Mosaics in all four IRAC channels, which consist of stacks of images taken between 2004 and 2007, and derived 5σ limiting magnitudes based on the faintest detected sources within a 40″ radius in point-spread function photometry catalogs constructed for M101 by K19. Our limiting (and absolute) magnitudes of $3.6 > 19.7$ (−9.5), $4.5 > 19.2$ (−10.0), $5.8 > 16.9$ (−12.3), and $8.0 > 15.9$ (−13.3) are sufficient to rule out an obscured progenitor as luminous and massive as those observed for the ILRTs mentioned in the previous paragraph. All of them had $M_{3.6} < −10$ before their outbursts.

One possibility is that SPIRITS 14aje was a heavily obscured core-collapse SN, similar to those presented in Jencson et al. (2017, 2018, 2019), but for which the luminous IR peak was missed during the gap in Spitzer/IRAC coverage between 2012 and the start of the SPIRITS survey in 2014. The red [3.6]–[4.5] color would not be unusual for a late-phase core-collapse SN (see, e.g., Tinyanont et al. 2016; Szalai et al. 2019; Jencson et al. 2019). The deep optical limits from iPTF shown in Figure 1 to $R > 21$ mag would then imply many magnitudes of extinction ($A_V > 9$ mag for an SN peak at $M_R = −16$ mag). Such high obscuration, perhaps by a dense molecular cloud, would explain the lack of a conspicuous progenitor star in the archival HST imaging. Still, given our relatively weak constraints on the timescale and peak brightness of 14aje, we are unable to confirm this scenario, and its definite nature thus remains elusive.

6.2. 17fe: Archetypal Slow SPRITE

The Spitzer IR light curves of SPIRITS 17fe in the Sculptor-group galaxy NGC 7793 ($d \approx 3.6$ Mpc) are shown in the middle panel of Figure 1. We caught it rising in brightness on 2017 February 16, and it had brightened another 0.8 mag on 2017 March 16. At that date, marking the maximum brightness seen in our data, it had apparent magnitudes of $3.6 = 16.52$

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20 http://hla.stsci.edu/hlaview_html
21 http://archive.stsci.edu/hst/hsc. In this paper we frequently give photometry for sources detected in HST images; in many cases these values are quoted from the HSC (see Whitmore et al. 2016, for an overview). HSC magnitudes are on the AB scale, and are determined using small photometric apertures. Throughout this paper we have corrected the HSC magnitudes to infinite apertures, using the values at https://archive.stsci.edu/hst/help/HSC_faq/cl_ap_cor_table_2016.txt. Where appropriate, we then converted the AB magnitudes to the Vega scale, using the zero-points for the WFC3 camera available at http://www.stsci.edu/hst/instrumentation/wfc3/data-analysis/photometric-calibration, and for the ACS camera from Sirianni et al. (2005).
and $[4.5] = 15.83$, corresponding to absolute magnitudes of $-11.3$ and $-11.9$, respectively. Subsequently, 17fe slowly faded until going below our detection limit in our final Spitzer observations on 2019 November 1. Thus the outburst duration was at least 988 days. There were no detections of this object prior to the 2017 outburst throughout the available Spitzer imaging at 3.6 and 4.5 $\mu$m, as shown by the upper limits in the middle panel of Figure 1. Also shown are the optical limits derived from the ATLAS forced-photometry light curves in the ATLAS-c and -o bands, which constrain the presence of an optical counterpart to $\lesssim 19$–$20$ AB mag in both bands for nearly the entire duration of the IR transient. We thus classify 17fe as a prototypical slow SPRITE—luminous in the IR, undetected in ground-based optical data.

The site of 17fe serendipitously lies within the HST field that we imaged for SPIRITS 15wt (discussed below in Section 7.5), for which our triggered observations were obtained on 2016 April 18. This was 304 days before our first Spitzer detection of the 17fe event. We astrometrically registered a Spitzer 4.5 $\mu$m difference-image frame, taken at 17fe’s maximum light, with an archival HST ACS $I$-band frame obtained in 2003 (GO-9774, PI S. Larsen). (The 2003 frame, rather than our 2016 image obtained with a WFC3 subarray, was chosen for the registration because of its larger FOV.) The top picture in

![Figure 2. HST images of the site of the fast SPRITE SPIRITS 14aje in M101. Top: color rendition of the site, from $B$, $V$, and $I$ images in the Hubble Legacy Archive. The frame is 29ʺ high (∼950 pc at the distance of M101). The site of 14aje, marked with a red cross, lies in a dust lane in a spiral arm of M101, with several rich young associations in the vicinity. Bottom row: zooms in on HST frames we obtained several months after the outburst, in $I$, $J$, and $H$. The site of 14aje from astrometric registration of the Spitzer and HST frames is marked with green 3σ error circles. None of the optical stars detected within the error circles in these frames appear to have varied in archival HST images taken at an epoch before, and an epoch after, the outburst (see text). Each frame is 5ʺ high. All HST images presented in this paper have north at the top, east on the left.](image)

| SPIRITS Designation | $t_0^a$ [MJD] | Max. Age$^b$ [days] | $\Delta t_{lc}^c$ [days] | $t_{peak}$ [MID] | $M_{[4.5]peak}$ [mag] | $M_{[3.6]–[4.5]}^d$ [mag] |
|---------------------|---------------|---------------------|--------------------------|------------------|----------------------|-------------------------|
| 14aje               | 56742.84      | 694.45              | 28.98                    | 56742.84         | 15.52 ± 0.03         | −13.6 ± 1.0             |
| 14axa               | 56821.90      | 122.43              | <258.75                  | 56821.90         | 16.28 ± 0.08         | −11.5 ± 0.1             |
| 17fe                | 57800.71      | 127.04              | 957.17                   | 57828.22         | 15.83 ± 0.04         | −10.9 ± 0.06            |

Notes.

$^a$ Time of the first Spitzer/IRAC detection.
$^b$ Maximum age of transient at the time of discovery, i.e., time between first detection and the previous nondetection.
$^c$ Time between first and last detections.
$^d$ Measured at the time of the light-curve peak, $t_{peak}$.
Figure 3 shows a color rendition of the site from the HLA. Like the fast SPRITE 14aje, the 17fe event occurred in a spiral arm of its host galaxy, with numerous young blue stars, red supergiants, and dust lanes in its vicinity. The frames in the middle row of Figure 3 zoom in on HST images taken before the outburst, in $I$, $J$, and $H$. The $I$ frame was taken 13.2 yr before the eruption, and $J$ and $H$ 0.8 yr before. The site of 17fe from astrometric registration of the Spitzer and HST frames is marked with green $3\sigma$ error circles. Each frame is $254''$ high. Bottom row: HST frames taken in $J$ and $H$ 0.8 yr after the maximum of the IR outburst, while the eruption was still underway. A near-IR counterpart is detected at $J$ and is bright at $H$.

Figure 3 shows a color rendition of the site from the HLA. Like the fast SPRITE 14aje, the 17fe event occurred in a spiral arm of its host galaxy, with numerous young blue stars, red supergiants, and dust lanes in its vicinity. The frames in the middle row of Figure 3 zoom in on HST images of the site, with green circles marking the $3\sigma$ location from the astrometric registration. From left to right, these frames show $I$ in 2003, and $J$ and $H$ from our own preoutburst observation in 2016. In addition to these frames, there are archival HST images in the $I$ band obtained in 2001 (two epochs: GO-8599, PI T. Boeker; and GO-9042, PI S. Smartt) and in 2014 (GO-13364, PI D. Calzetti). There were no changes in brightness of any objects inside the error circle in all of these preoutburst images. Outside the error circles on the southwest side is a bright red star, which is a high-amplitude variable in the HST frames; however, it is too far outside the circle to be related to 17fe.

In addition to the preoutburst HST images, there are fortuitous archival WFC3/IR frames obtained in the $J$ and $H$ bandpasses on 2018 January 16 (GO-15330, PI D. Calzetti), 306 days after the date of the IR maximum. The IR outburst was still underway at this epoch. Cutouts from these frames are shown in the bottom row of Figure 3. A faint, very red object has appeared near the center of the astrometric error circle at both wavelengths, making it a very likely near-IR counterpart of the SPRITE in outburst. Based on aperture photometry relative to HSC stars in the nearby field, we find Vega-scale magnitudes for this star of $J = 24.2$ and $H = 21.4$. There is a hint that this object is present in our 2016 preoutburst $J$ and $H$ frames, but the field is crowded with overlapping faint stars. There is no convincing progenitor in the preoutburst $I$ frames; there is a partially resolved star inside the error circle in the 2003 $I$-band image just southwest of the center, with a Vega-scale magnitude of $I \approx 27.1$. However, this star does not coincide with the object that appeared in the 2018 frames.

In Figure 4, we show the spectral energy distribution (SED) of 17fe, constructed from the 2018 January 16 WFC3/IR detections and interpolations of the Spitzer/IRAC [3.6] and [4.5] light curves to the same epoch, 333 days after the first
detection of the event with Spitzer. The SED is very red, appearing to peak in the IR around 3 \mu m, at a band luminosity of \lambda L_\lambda \sim 10^9 L_\odot. The near- to mid-IR SED can be approximated by a blackbody spectrum of temperature \(T_{BB} \approx 1050\) K. We also tried fitting the HST and Spitzer points with two separate blackbodies. In this case, the HST data alone indicate a slightly warmer temperature of \(T_{BB} \approx 1290\) K; however, there is not strong evidence for two components. These values are near the temperatures for dust condensation (e.g., Ney & Hatfield 1978; Gehrz et al. 1980a), suggesting the presence of newly formed, warm dust.

A stellar merger is a compelling scenario for the origin of LRNe and at least some slow SPRITEs. For SPRITEs like 17fe, early dust formation is required to obscure or dramatically shorten the associated OT. In models by Pejcha et al. (2016a, 2016b), elaborated by Metzger & Pejcha (2017), the secondary light-curve peak seen in many LRNe can be explained by the shock interaction of the dynamical merger ejecta with equatorially concentrated material ejected from the binary during the pre-dynamical in-spiral phase. The dense, rapidly cooling regions behind radiative shocks are favorable locations for dust formation. Metzger & Pejcha (2017) find that, for certain binary configurations, namely, those involving giant stars and having long phases of premerger mass loss, dust may form early enough to completely obscure the associated shock-powered transient at optical wavelengths.

For a similar, but more luminous, slowly evolving IR transient, SPIRITS 19fi, an associated faint, short-duration (\approx 10 days), red OT was detected in stacked observations from the Zwicky Transient Facility (see J20). For two other slow SPRITEs, SPIRITS 17ar and SPIRITS 18nu, their near-IR outburst spectra show strong molecular absorption features akin to those of a late M giant (J. Jencson et al., 2022 in preparation). These features are also seen in late-time spectra of several optically bright LRNe (e.g., Kamiński et al. 2015; Blagorodnova et al. 2017, 2020). These observations, together with the late-time SED of SPIRITS 17fe suggestive of warm dust, lend credence to a stellar merger accompanied by early dust formation as a viable origin of many slow SPRITEs.

### 6.3. 14axa: Classical Nova?

SPIRITS 14axa in M81 (\(d \approx 3.6\) Mpc) was initially classified by us (K17) as a fast SPRITE. We detected it with Spitzer at only one epoch, 2014 June 13, as shown by its light curve in the right-hand panel of Figure 1. There were Spitzer nondetections 122 days before this observation (2014 February 11), and 239 days afterward (2015 February 7). Our triggered HST observations on 2014 September 26 were obtained between the dates of the Spitzer detection and the subsequent nondetection, so it is unknown whether the IR event was still underway. The absolute magnitude at the single Spitzer detection was \(M_{\text{IR}} \approx -11.5\).

We learned later that this event had also been detected at optical wavelengths and reported as a CN, designated PNV J09560160+6903126. The initial discovery was by Hornoch & Kucakova (2014), who reported an unfiltered (approximately \(R\)) optical magnitude of 18.9, on 2014 May 21.9. The transient had been fainter than magnitude 21.7 two nights earlier, demonstrating an extremely fast rise time. Five nights later, Hornoch et al. (2014) observed the object with a wide-field camera on the 2.5 m Isaac Newton Telescope. A narrow-band filter confirmed strong emission at H\alpha, and yielded a Sloan \(r'\) magnitude of 19.6. All of this information is consistent with the transient being a CN, although to our knowledge there is no direct spectroscopic confirmation of this conclusion. Our detection with Spitzer suggests that the nova was in a dust-forming postmaximum phase at the time of our observation.

The site of 14axa lies between two spiral arms of M81, in a crowded sheet of stars that appears to lack a young population (in contrast to most of the SPIRITS IR transients, which strongly tend to be associated with spiral arms, young associations, and dusty environments). There are three available \(I\)-band HST images of the site, two obtained with ACS in 2002 and 2004 (GO-9353, PI S. Smartt, and GO-10250, PI J. Huchra), and our triggered WFC3 observation in 2014. We performed an astrometric registration of the Spitzer 4.5\mu m image showing 14axa with the 2004 ACS image, in order to locate the site in the HST frames. Figure 5 shows renditions of the three \(I\)-band frames, with green circles marking the 3\sigma error positional locations. Not far from the centers of the circles is a faint star that noticeably brightened in the 2014 image. Approximate \(I\) magnitudes (AB scale), determined from aperture photometry relative to nearby stars with HSC magnitudes, are 25.2 in 2002, 25.8 in 2004, and 24.7 in 2014. (In our 2014 \(J\) and \(H\) frames, the object is badly blended with the neighboring star to the northeast.) The \(I\)-band luminosity at the 2014 observation is consistent with a CN about four months past maximum; see, for example, the \(I\) band and near-IR light curves of T Pyx presented by Walter et al. (2012) and Evans & Gehrz (2012). However, the preoutburst object is unusually luminous compared to the progenitors of

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22 We are grateful to D. Bishop for maintaining a website devoted to extragalactic novae, at https://www.rochesterastronomy.org/novae.html, which alerted us to this optical detection. The apparent coincidence of 14axa with the nova was also noted by Oskinova et al. (2018).
typical CNe. Unless it is a chance superposition, the preoutburst detection suggests that the binary system has a red-giant donor star, similar to Galactic precursors such as T Pyx and RS Oph (e.g., see the reviews of Schaefer 2010; Mukai 2015). The object was below detection in archival preoutburst HST images at the V band, showing that it was indeed red.

As discussed in J20, the majority of SPIRITS transients fainter than $M_{[4.5]} \approx -12.5$ at peak are similar to 14axa; that is, they were detected only within a single Spitzer visibility window—implying an evolutionary timescale $\lesssim 6$ months. At their peak they have red IR colors of $[3.6] - [4.5]$ between 0.5 and 1.2. Two events, SPIRITS 15bb and SPIRITS 15bh, were also preceded by short ($\lesssim 2$ months), faint ($M_I \approx -8$) optical outbursts recovered in stacked, archival iPTF images. All 15 of these fast and faint IR transients in SPIRITS were found in just seven galaxies within $\approx 5$ Mpc, and nearly half of them were in M81. This high rate from a small number of the nearest galaxies suggests they are common events. CNe are thus an attractive scenario for their origin; the rate in large galaxies like the Milky Way is estimated to be $\approx 40-80$ yr$^{-1}$ (e.g., Shafter 2017; De et al. 2021). As with 14axa, the optical precursors detected for 15bb and 15bh were in the luminosity range typical of novae, further supporting this hypothesis.

Some novae, namely, those of the DQ Her class, such as NQ Vul (Ney & Hatfield 1978), LW Ser (Gehrz et al. 1980a), and V705 Cas (Gehrz et al. 1995a; Evans et al. 1997, 2005), form optically thick dust shells, while others that form optically thin shells still produce strong IR emission, peaking on a timescale of $\approx 50-80$ days at $M_{[4.5]} \approx -11$ to $-12.5$ (e.g., V1668 Cyg; Gehrz et al. 1980b). These properties are generally consistent with the fast and faint IR transients discovered by SPIRITS (J20). Further study on the implications of this population for the rate of strongly dust-forming novae and their impact on the chemical enrichment and dust budget of galaxies (e.g., Gehrz 1988, 1999; Evans et al. 2012) is thus warranted. A less likely alternative is that this was the coronal-emission phase of an ONe nova such as QU Vul (Greenhouse et al. 1988, 1990). These novae appear to be several absolute magnitudes fainter at $4.5 \mu m$ during maximum light than dusty novae (see, e.g., Gehrz et al. 1995b).

7. Luminous Periodic Infrared Variables

As noted above (Section 2), a significant fraction of the suspected transients discovered early in the SPIRITS survey proved eventually to be periodic, or likely periodic, variables when more Spitzer data, over longer time baselines, had accumulated. The periods associated with these sources are nearly all longer than 1000 days. This led to us triggering HST observations of variables that were only recognized as being periodic later on. In typical cases, the objects were in the rising phase of their light curves during the first few SPIRITS observations, leading to our initial classifications of them as candidate SPRITEs.

In view of the importance of the periodicity to understanding these sources, we first summarize our analysis of the Spitzer photometry and the consequent insight into the nature of this sample of periodic sources. We then describe the HST observations of individual objects and the additional understanding they provide.

Characteristics of the periodic and likely periodic variables that we observed with HST are summarized in Table 4. We derived the periods given in column 2 from the Spitzer light curves using the procedure described in K19 (which in turn follows VanderPlas & Ivezic 2015), allowing the $[3.6]$ and $[4.5]$ magnitudes to be analyzed simultaneously. Two of the variables have periods quoted as lower limits, because there is Spitzer photometry covering only about a single cycle. Coverage of the other sources is rather better than for most of the variables discussed by K19, although few have complete coverage for as much as two cycles. Given that Mira light curves are known not to repeat exactly from cycle to cycle, our derived periods can only be good to about 5%-10%, and are best judged by examining the individual light curves. The mean apparent magnitudes (denoted $[3.6]$ and $[4.5]$) are given in columns 3 and 5, the peak-to-peak amplitudes ($\Delta [3.6]$ and $\Delta [4.5]$) in columns 4 and 6, and the mean colors ([3.6] – [4.5]) in column 7. Columns 8 and 9 give the mean absolute
only one pulsation cycle or less has been covered. Red points mark the periodic variables from K19, and cyan squares the LMC OH/IR stars from Goldman et al. (2017). The isolated and unusually luminous black point is SPIRITS 15mr (see Section 7.6).

![Figure 6. Mean [4.5] absolute magnitude vs. pulsation period for the periodic and suspected periodic variables from this paper, shown as black points, or gray points if only one pulsation cycle or less has been covered. Red points mark the periodic variables from K19, and cyan squares the LMC OH/IR stars from Goldman et al. (2017). The isolated and unusually luminous black point is SPIRITS 15mr (see Section 7.6).](image)

Table 4

| SPIRITS Designation | Period [days] | [3.6] \(\Delta \) [mag] | [4.5] \(\Delta \) [mag] | [3.6] \(\Delta \) [4.5] | [3.6] – [4.5] | \(M_{[3.6]}\) [mag] | \(M_{[4.5]}\) [mag] |
|---------------------|--------------|---------------------------|---------------------------|---------------------------|---------------------------|------------------|------------------|
| 15n\(a\)            | 1614         | ...                       | 16.66                     | 1.07                      | 1.5                       | ...              | –12.17           |
| 15qa                | 1232         | 16.69                     | 16.11                     | 1.43                      | 0.58                      | –11.45           | –11.68           |
| 15aag               | 1233         | 18.10                     | 17.07                     | 1.55                      | 1.04                      | –10.04           | –11.07           |
| 15ahg\(a\)          | 1163         | 16.49                     | 16.13                     | 1.16                      | 0.36                      | –11.02           | –11.38           |
| 14al                | ~2160        | 16.60                     | 15.20                     | 0.82                      | 1.40                      | –10.91           | –12.31           |
| 14dd                | 1418         | 16.89                     | 15.92                     | 1.11                      | 0.97                      | –10.62           | –11.59           |
| 15afp               | ~1650        | 17.63                     | 16.87                     | 1.13                      | 0.76                      | –10.64           | –11.40           |
| 15wt\(c\)           | 1188         | 16.55                     | 16.03                     | 0.94                      | 0.53                      | –11.16           | –12.17           |
| 14bb\(c\)           | 1498         | 16.29                     | 15.57                     | 1.13                      | 0.71                      | –11.48           | –12.20           |
| 15mr\(a\)           | 1113         | 15.71                     | 14.96                     | 1.32                      | 0.76                      | –13.01           | –13.76           |
| 15mr\(c\)           | ~1800        | 16.86                     | 16.69                     | 2.16                      | 0.17                      | –11.86           | –12.03           |
| 16ea\(b,e\)         | ~670         | ...                       | 16.51                     | 1.11                      | 1.6                       | ...              | –10.83           |

Notes.

\(a\) [3.6] and [4.5] denote the mean apparent magnitudes of the variables, and \(\Delta [3.6]\) and \(\Delta [4.5]\) denote the peak-to-peak amplitudes of their variations.

\(b\) Insufficient data at [3.6] to determine the mean magnitude, amplitude, and absolute magnitude over the pulsation cycle (see text). The approximate color given in column 7 is based on an estimate of the likely mean [3.6] magnitude.

\(c\) 15ahg, 15wt, 14bbc, 15mr, and 15mt had detected or suspected optical/near-IR counterparts in HST imaging (see text). 16ea is equivocal (see Section 7.7). The others had no convincing counterparts at I, J, or H in HST images.

magnitudes at [3.6] and [4.5], calculated using the distance moduli in Table 2. The absolute magnitudes cover the range \(-11.07 > M_{[4.5]} > -12.31\), except for one unusually luminous variable, 15mr, at \(M_{[4.5]} \approx -13.76\).

A similar class of luminous periodic IR variables discovered in nearby galaxies by SPIRITS was discussed by K19; they suggested that some of these objects are related to the dusty OH/IR stars (intermediate-mass, oxygen-rich Mira variables) found in our Galaxy and the LMC. In Figure 6 we plot the period–luminosity relation for our variables, using filled gray circles for objects with one variation cycle or less, and filled black circles for those with more. Also plotted are the data from K19 for SPIRITS periodic variables in nearby galaxies (filled red circles), and for LMC OH/IR stars from Goldman et al. (2017; filled cyan squares). All but one of our variables fall on, or close to, the clump of variables that K19 identify with intermediate-mass AGB stars (1000 < \(P < 2000\) days and \(-11 > M_{[4.5]} > -13\)), and which itself falls close to the extrapolated period–luminosity relation found for Mira variables in the LMC (Riebel et al. 2015; Whitelock et al. 2017). These sources have large variation amplitudes (e.g., K19, their Figure 4), as do our sources that are in the approximate range \(0.8 < \Delta [4.5] < 2.2\) mag. The range of colors, \(0.17 < [3.6] – [4.5] < 1.5\), is also comparable to the values discussed by K19 (see their Figure 5). Footnotes in column 1 of Table 4 mark the five variables with HST detections or possible detections, as we discuss later in this section.

Most of these variables have extremely red Spitzer colors, indicating very low effective temperatures and circumstellar dust, a consequence of high mass-loss rates. For example, colors of \([3.6] – [4.5] \approx 0.6, 1.0, and 1.5\) correspond to blackbody temperatures of \(~1000, 800, and 500\) K, respectively (see Figure 7 in K19).

At such very low effective temperatures, we generally would not expect to detect these objects with our one-orbit HST observations. In a typical case of a variable with an apparent
IRAC channel 2 magnitude of $[4.5] \simeq 16.5$, and the nominal exposure times we used for our HST observations (Section 3), the WFC3 ETC indicates that the source would not be detected ($S/N < 5$) in the HST/WFC3 $I$, $J$, or $H$ bandpasses if its blackbody temperature was below $\sim 750$ K. Above 750 K it would be detectable only at $H$. For a temperature above 850 K, it would be detected also at $J$. For detection at $I$, a source with $[4.5] = 16.5$ would have to be hotter than $\sim 1275$ K. However, the use of blackbodies in these estimates is only a rough approximation, as OH/IR stars have strong molecular absorptions, due to H$_2$O and CO in particular, which influence the $[3.6]-[4.5]$ and other colors. Moreover, these estimates are optimistic, as they neglect background light and dust extinction.

It is also possible to estimate the anticipated HST magnitudes, using what is known about the LMC OH/IR stars that are illustrated in Figure 6, and assuming that our variables are similar. We use the $JHK(L)$ light curves for these OH/IR stars from Whitelock et al. (2003) and $I$-band light curves from Soszyński et al. (2009); note, however, that the very reddest LMC sources were not detected in the ground-based $I$ or $H$ bands. Unfortunately there is only single-epoch Spitzer photometry for these, so we do not have mean Spitzer magnitudes or colors. The single-epoch colors are in the range $0.3 < [3.6] - [4.5] < 0.8$ for the AGB stars, and $[3.6] - [4.5] = 0.9$ for the single supergiant. The AGB amplitudes are in the ranges $1.5 < \Delta H < 1.9$ and $2.8 < \Delta I < 4.0$, while the supergiant has $\Delta H = 0.4$ and $\Delta I = 1.5$. The very large amplitudes of the AGB variables, particularly at the shortest wavelengths, complicate any predictions of HST flux. Furthermore the Goldman et al. (2018) comparison of the SMC with the LMC suggests that the mass-loss rates of these O-rich stars are a function of the
metallicity; therefore it seems likely that the AGB stars under
discussion will have thicker shells than similar stars in the LMC
and thus fainter magnitudes at HST wavelengths. Nevertheless,
these provide a useful comparison and the following ranges of
colors found for the LMC sources are used to estimate the
expected HST magnitudes for our sources: $7.6 < (I - 4.5) < 10.7$ and $2.6 < H - [4.5] < 4.8$. However, additional dust
extinction is possible and will make the HST magnitudes even
fainter than these values would predict.

We also note that there are significant differences between
the bandpasses of the ground-based $I_{IIHK}$ filters and the similar
filters used by HST. Although these differences are potentially
problematic, particularly for cool stars with extended atmo-
spheres where strong molecular absorption dominates the
colors, they are not important for the comparisons made here,
where the large-amplitude variations dominate.

We now discuss the individual periodic and likely periodic
variables that we imaged with HST. Their Spitzer light curves are
collected in Figure 7.

7.1. 15nz

SPIRITS 15nz was announced by Jencson et al. (2015) as a
possible IR transient in M83 ($d \approx 4.7$ Mpc), based on our initial
few SPIRITS observations. These data showed a slowly rising
[4.5] luminosity during 2014 and early 2015. In response to
this announcement, a separate team (GO-14463, PI B. McCollum) obtained HST imaging of the site. Since 2015 we have accumulated additional IR observations, and there are also archival Spitzer data obtained in 2010. The IR light curves of 15nz are shown in the top left panel of Figure 7. The data at [4.5] indicate a period close to 1600 days. There are insufficient [3.6] detections to analyze for periodicity, but they can be used for an estimate of the color, which at [3.6] - [4.5] ~ 1.5 makes 15nz the reddest of the periodic variables discussed in this section.

As noted in the introduction to this section, detection of a
source as cool as 15nz at HST wavelengths is not expected. We
registered a Spitzer frame taken at maximum brightness with
HST frames to find the precise location of the variable in the
latter. At this site in the disk of M83 there is a dense sheet of
faint stars. There are several faint objects within a $3\sigma$ error
circle, but comparing $I$-band frames taken at three epochs
(2009, 2010, 2016), we see no significant variation of any of
these stars. Only two epochs of HST imaging at $J$ and $H$ are
available (2009, 2016), but again we see no variation of any
detected stars within the error circle. It thus appears that, as was
expected, 15nz has no optical or near-IR HST counterpart at $I$,
$J$, and $H$. From a comparison with the OH/IR stars in the LMC,
we would expect 15nz to have $I > 27.4$ and $H > 21.5$, or
probably much fainter given how red it is.

7.2. 15qo and 15aag

SPIRITS 15qo was likewise announced by Jencson et al.
(2015) as an IR transient, lying in NGC 1313 ($d \approx 4.2$ Mpc). A second transient or variable in the same galaxy,
SPIRITS 15aag, was announced by Jencson et al. (2016a); it
lies only 54" away from 15qo. We adjusted our HST pointing
so as to capture both of these objects in the same image frames.

The Spitzer light curves of these two variables are shown in
the top middle and top right frames of Figure 7. As in the case
of 15nz, both objects were caught in rising phases in the first
few SPIRITS observations, and were announced as transients.
However, as the light curves show, they later proved to be
periodic variables. Curiously, their pulsation periods are nearly
the same, both being about 1230 days, and they are also nearly
in phase. They are, however, definitely distinct objects.

We registered a Spitzer image showing both objects near
maximum light with archival HST images as well as the new
images obtained in our program. At the site of 15qo there is an
extremely rich star field, lying in an actively star-forming
region in NGC 1313. Several faint stars fall within a $3\sigma$ error
circle, including a bluish star near the center. None of these
stars appear to be significantly variable in the $I$-band frames
taken in 1994, 2003, 2004 (two epochs), and 2016. Our $J$ and $H$
frames show no very red star at the site. We conclude that there is
no detectable optical/near-IR counterpart.

The results are similar for 15aag, which is significantly
redder than 15qo. It also lies in a rich field, not far from several
H II regions. There is again a faint star within the $3\sigma$ error
circle, which showed no significant variability in the $I$-band
frames taken in 2001, 2003, 2004 (two epochs), and 2016. This
star is detected in our $J$ and $H$ observations, but the source is
not extremely red; unfortunately these are the only frames in
$J$ and $H$ in the HST archive. As in the case of 15qo, we find no
convincing optical/near-IR counterpart.

7.3. 15ahg, 14al, and 14dd

SPIRITS 15ahg is another object announced as an IR
transient by Jencson et al. (2016a), lying in the M81-group
spiral galaxy NGC 2403 ($d \approx 3.2$ Mpc). Two previously
identified variables in the SPIRITS database, 14al and 14dd,
lie close to the position of 15ahg, and we adjusted the telescope
pointing so that we could include all three in the HST frames.
The site of these variables lies near a spiral arm on the
northwest side of NGC 2403, in an extremely rich star field.
Several giant H II regions are nearby.

The Spitzer light curves of 15ahg are shown in the left panel
in the second row of Figure 7. Its period is about 1160 days,
and it is relatively blue, with a mean [3.6] - [4.5] = 0.36 There
are two $I$-band HST observations of this site in the archive, one
taken in 2005 (GO-10402, PI R. Chandar), and the other is our
frame obtained in 2016. We registered these images with a
Spitzer IRAC channel 2 frame from the SPIRITS program,
taken near maximum brightness of 15ahg. Inside the $3\sigma$ error
circle in the $I$-band frames is a faint star that brightened
significantly from 2005 to 2016, consistent with the phasing
of the IR variability shown in Figure 7. In the 2005 image, the
variable lies in a blended clump of several faint stars, which is
possibly a compact sparse cluster. In 2016 it had risen to an
HST $I$ magnitude of about 24.5 (Vega scale, based on aperture
photometry relative to several HSC stars in the field). This star
is optically very red and is well detected in our $J$ and $H$ frames.
The HSC Vega-scale $J$ and $H$ magnitudes for the object are
20.79 and 18.94, respectively. Thus there is little doubt that this
object is the optical/near-IR counterpart of the Spitzer variable.
The four panels in Figure 8 show small postage stamps from the
two $I$-band frames (top row), and from our $J$ and $H$ images
(bottom row). The astrometric $3\sigma$ error circle is shown in green
in the top two frames.

A comparison with the LMC OH/IR stars (see introduction
to this section) would predict $18.7 < H < 20.9$ and
$1.1 < (J-H) < 2.0$ for 15ahg. These are consistent with the
measured $H \approx 18.9$ and $J - H \approx 1.8$ and support our suggestion that this object is a pulsating AGB variable.

The light curves of 14al and 14dd are shown in the second and third panels in the second row of Figure 7. 14al is extremely red, with a mean $[3.6] - [4.5] = 1.4$, and its approximate period, 2160 days (5.9 yr), is the longest of any of the periodic variables. Its peak-to-peak amplitudes, $\Delta[3.6] \approx 1.0$ and $\Delta[4.5] \approx 0.8$ mag, although slightly less than those of the other periodic variables, are still large. 14al lies in a rich star field. There are several faint stars at the site, but none varied significantly in the I frames from 2005 and 2016. None of them are bright at $J$ and $H$. We conclude that there is no convincing optical/near-IR counterpart.

14dd is another likely periodic variable, with a period of 1420 days and a red color of $[3.6] - [4.5] \approx 1.0$. As in the case of the nearby 14al, there are no variable objects at the site in the two available HST I-band frames, nor any conspicuous objects within the error circle at $J$ and $H$. Again, we find no credible optical/near-IR counterpart of this very cool object.

### 7.4. 15afp

The IR light curves of SPIRITS 15afp are shown in the lefthand panel in the third row of Figure 7. This object rose by over one magnitude from the first SPIRITS observation in 2014 to a peak in late 2015, leading us to announce it as a candidate transient (Jencson et al. 2016a). We triggered our HST imaging in 2016 March. 15afp lies in a spiral arm of the face-on and actively star-forming galaxy NGC 6946 ($d \approx 4.5$ Mpc). This variable could be periodic, but our observations cover less than one cycle of a period of around 1650 days. We also note our photometry is likely contaminated by another nearby, but unrelated, variable source. The amplitudes and color are similar to the other periodic variables discussed in this section. However, we cannot rule out that the object is a slow SPRITE transient, based on our relatively limited data.

We registered a Spitzer image taken at the maximum brightness of 15afp with an ACS I-band frame obtained in 2016 October (GO-14786, PI B. Williams). The site lies in a dense sheet of stars, with moderately high extinction. There are several faint stars within a 3$\sigma$ error circle. None of them appeared to vary between the ACS frame and our own WFC3 I-band frame taken seven months earlier, nor in comparison with a shallow ACS frame obtained in 2004 (GO-9788, PI L. Ho). There are no conspicuous sources at the site in our J and H frames. On the basis of these fairly limited data, we see no convincing evidence of an optical or near-IR counterpart.

### 7.5. 15wt and 14bbc

The Spitzer light curves of SPIRITS 15wt are plotted in the middle panel in the third row of Figure 7. 15wt rose by nearly 1 mag over the first two years of SPIRITS observations of the host galaxy, NGC 7793, in the nearby Sculptor Group (d $\approx 3.6$ Mpc). This slow eruption of an apparent transient prompted us to trigger our HST imaging, obtained on 2016 April 18. However, our subsequent observations, as well as archival data, clearly reveal that 15wt is actually a periodic variable of the type discussed by K19, with a well-determined period of 1190 days. It is relatively “blue,” with a mean color of $[3.6] - [4.5] \approx 0.5$.

We registered an archival HST/ACS I-band image of NGC 7793 obtained on 2003 December 10 (GO-9774, PI S. Larsen) with a Spitzer frame taken near maximum brightness of 15wt, in order to locate the site in the HST frames. We then registered the ACS frame with WFC3 I-band frames taken on
and on 2016 April 18 in our own program. Just inside the 3σ registration error circle is a star that was not detected in 2003 and 2014, but had brightened in 2016. This object is very bright in the J and H frames that we obtained at the same time as our I image in 2016, and the date of the HST imaging is close to the time of maximum brightness in the Spitzer frames. Thus we conclude that the optical/near-IR object is the counterpart of the IR variable. In confirmation, there are also archival WFC3/IR frames of the site taken on 2018 January 16 in J and H (GO-15330, PI D. Calzetti), when the IR variable was near minimum light, as shown in Figure 7. The counterpart is significantly fainter in these frames than in 2016.

Figure 9 presents false-color renditions of the I-band frames from 2014 and 2016 in the top row, revealing the star just inside the error circle that brightened in 2016. The bottom row shows that this star is very bright in J and H, in the WFC3 frames taken during our same HST visit in 2016. The HSC gives the following magnitudes (Vega scale) for this object at the 2016 epoch: $I = 24.23$, $J = 20.25$, and $H = 18.70$. The LMC OH/IR stars (see introduction to this section) would have $26.7 > I > 23.6$ and $20.8 > H > 18.6$ at this distance, consistent with our suggestion that the Spitzer variable and its HST optical/near-IR counterpart is a pulsating AGB star.

Another IR variable, 14bbc, had been discovered earlier during the SPIRITS program. It lies close to the position of 15wt, and we adjusted the HST pointing for our triggered observation in 2016 so as to include both 15wt and 14bbc in the images. The Spitzer light curves of 14bbc are shown in the right-hand panel in the third row of Figure 7. This is another periodic variable, which has undergone two full cycles during the archival and SPIRITS Spitzer observations (plus an earlier observation in 2004). Its period is 1500 days, and its color is $([3.6] − [4.5]) \approx 0.7$.

The site of 14bbc lies in an extremely dense star field in a spiral arm of NGC 7793. We located the site in the available HST images through astrometric registration, as just described for 15wt. As shown in the I-band frame in the left panel of Figure 10, there are several faint stars inside the 3σ error circle. None of them varied between archival HST frames obtained in

Figure 10. False-color renditions of HST WFC3 images of the site of the periodic IR variable SPIRITS 14bbc in NGC 7793, obtained on 2016 April 18. From left to right the frames were taken in $I$, $J$, and $H$. The green circle in the $I$ image is the 3σ error position of the Spitzer variable. As discussed in the text, here is no obvious counterpart of 14bbc in the $I$ frame (none of the faint stars inside the circle varied across several HST epochs), but it is detected at $J$ and is bright at $H$. The height of each frame is 2".
2003, 2014, and our own frames from 2016, and we believe the variable was not detected in the I band. However, as shown in the figure, a blended source does appear in the J frame, and it is bright at H; the HSC gives a Vega-scale magnitude for this object of $H = 19.42$. In the archival frames obtained on 2018 January 16 used for 15wt, the candidate has faded significantly at both J and H, consistent with the phasing of 14bbc seen in Figure 7. Based on its extremely red optical color, location near the center of the error circle, and variability at J and H, we conclude that this star is the near-IR counterpart of the Spitzer variable. Its magnitude is consistent with the $20.4 > H > 18.2$ anticipated for an AGB variable at the distance of NGC 7793, using the LMC OH/IR star colors (see introduction to this section).

7.6. 15mr and 15mt

The IR variability of SPIRITS 15mr was reported by Jencson et al. (2015), who suggested it as a transient and possible SPRITE. It belongs to the star-forming barred spiral galaxy NGC 4605 ($d \approx 5.5$ Mpc). Another SPIRITS variable, 15mt, lies nearby, and for our triggered HST observation on 2016 June 14 we adjusted the telescope pointing to include both objects. The Spitzer light curves of both variables are plotted in the bottom left and bottom middle panels in Figure 7. As the figure shows, both objects were rising in brightness up to the date of our 2016 HST imaging, leading at that time to our classification of both as possible transients. However, our subsequent observations show that 15mr is a periodic variable that has gone through two cycles, with a period of 1110 days.

The position of 15mr in the period–luminosity relation (Figure 6) shows it to be about 2 mag brighter than the other sources with similar periods. However, its color, $[3.6] - [4.5] \approx 0.8$, and peak-to-peak amplitudes, $\Delta [3.6] = 1.4$ and $\Delta [4.5] = 1.3$, are very similar to those of the other pulsators. As Figure 6 shows, a few of the variables in K19 also lie in this region of the period–luminosity relation. The nature of these luminous variables is unclear, although this is where we expect to find mass-losing red supergiants. The LMC OH/IR supergiant, IRAS 04553–6825, the most luminous source from Goldman et al. (2017), is an example of this population.

15mt is also an apparent periodic variable with a longer period ($\sim 1800$ days), but the classification is less certain because it has only gone through a single cycle in the available Spitzer data. It has a very “blue” IR color, $[3.6] - [4.5] \approx 0.2$, and especially large peak-to-peak amplitudes, $\Delta [3.6] \approx 1.7$ and $\Delta [4.5] \approx 2.2$.

We registered a Spitzer IRAC 4.5 $\mu$m frame from 2016 April, showing both 15mr and 15mt near maximum brightness, with an archival HST WFC3 I-band image obtained in 2013 (GO-13364, PI D. Calzetti), and we compared the 2013 image with our triggered frame taken in 2016. 15mr lies in a rich star field with moderate extinction, with several young associations in the vicinity. As shown in the top left image of Figure 11, inside the $3\sigma$ registration error circle are several resolved stars and numerous, partially resolved fainter objects. The site lies near or within a rich young association to the southwest, from which it is separated by a dark dust lane. The brightest star within the error circle is also bright in H, as shown in the top right image in Figure 11, making it a candidate counterpart of 15mr. However, this star is not especially red at optical wavelengths and is even detected in the $u$ band (F336W filter); the HSC gives magnitudes (Vega scale) of $u = 23.39$, $B = 24.12$, $V = 23.70$, and $I = 22.99$. Yet the object also has a near-IR excess, as shown by the HSC Vega-scale magnitude of $H = 20.36$. By comparing the two available I-band images from 2013 and 2016, we see no significant variation of this star. Without further information, it remains unclear whether the bluish star represents a binary companion of, or a chance alignment with, the IR variable, or whether the situation is more complicated. The LMC OH/IR supergiant mentioned...
above, IRAS 04553–6825, has $I - [4.5] \approx 8.7$ and $H - [4.5] \approx 3.8$, so 15mr would be expected to have $I \approx 23.7$ and $H \approx 18.8$. Taking into account the limited information we have on supergiant colors and 15mr’s large amplitude, the measured $H = 20.36$ cannot be used to rule out the possibility that it is an OH/IR supergiant. The shorter-wavelength magnitudes may be too bright for the OH/IR supergiant interpretation, but, as already noted, they could plausibly originate from a chance alignment in this rich star field, or conceivably a binary companion.

15mt also lies in a rich field, overlain with clumpy dust absorption, as shown in the $I$-band image in the bottom left frame in Figure 11. There are several resolved stars inside the 3σ error circle, and a brighter star on the northeast side just outside the circle. The $H$-band image in the lower right panel in the figure shows two partially resolved bright stars, one corresponding to the bright $I$-band star just outside the circle. This bright star is extremely red; its Vega-scale HSC magnitudes are $V = 25.18$, $I = 22.47$, and $H = 19.44$, making it a plausible optical/near-IR counterpart of 15mt—especially as the variable’s $[3.6] - [4.5]$ color is relatively “blue.” However, we see no significant variation of this star in the $I$ band between 2013 and 2016. The second $H$-band star, just inside the error circle, appears to be undetected in the $I$ frame. An LMC OH/IR AGB star (see introduction to this section) would have $27.4 > I > 24.3$ and $21.5 > H > 19.3$, so it seems possible that the star measured is the Spitzer source, but that it is confused at shorter wavelengths by bluer stars. Alternatively the second $H$-band star may be the Spitzer source. 15mt is discussed further in the summary below.

### 7.7. 16ea

SPIRITS 16ea was announced by Jencson et al. (2016b) as a possible IR transient in the nearby starburst irregular galaxy NGC 4214 ($d \approx 2.9$ Mpc). In response to this publication, a separate team (GO-14892, PI B. McCollum) obtained HST imaging observations of the site of 16ea with WFC3.

The Spitzer light curves of 16ea are plotted in the bottom right panel of Figure 7. Unfortunately, the quality of the light curves is relatively poor and difficult to interpret. This is due to the presence of many image and subtraction artifacts in the vicinity of 16ea in our difference images, leading to large uncertainties and numerous nondetections. Still, the handful of detections at [4.5] show evidence of multiple peaks, consistent with a periodic variable. Hence we classify it as probably periodic, although the properties listed in Table 4 should be viewed with caution. The inferred color (from the limited [3.6] detections) is very red at $[3.6] - [4.5] = 1.6$ mag. The HST observations in GO-14892 were obtained on 2017 May 17 and 21; unfortunately this imaging was done only in the WFC3 IR channel. The status of the variable at this epoch is uncertain, but it appears to have been near a minimum in the pulsation cycle.

We astrometrically registered a Spitzer 4.5 μm difference image with an archival HST WFC3 $I$-band frame obtained on 2009 December 23 (GO-11360, PI R. O’Connell). Images in the WFC3 IR channel $J$ and $H$ bandpasses were obtained at the same time in the O’Connell program. Figure 12 shows false-color renditions of the 16ea site from these $IJH$ frames, with the 3σ registration error circle shown in the left panel. Inside the circle is a bright star, which is very red, making it a plausible optical and near-IR counterpart of 16ea. The HSC gives magnitudes (adjusted to Vega scale) for this star of $I = 22.30$, $J = 20.75$, and $H = 19.88$. In comparison with an ACS $I$-band image of the site obtained on 2004 October 24 (GO-10332, PI H. Ford), we see no significant change in the brightness of this candidate. Comparing the 2009 and 2017 frames in $J$ and $H$, there is again no compelling evidence for variability. Given the fragmentary data from both HST and Spitzer, it is difficult to reach firm conclusions about this object, beyond our identification of a probable optical/near-IR counterpart.

#### 7.8. Periodic Variables: Discussion

The analysis of the Spitzer data for the periodic variables suggests that the majority (at least nine) of them are highly evolved AGB stars, similar to those discussed by K19 and to the OH/IR AGB variables in the Galaxy and LMC. Where we have HST detections they support this conclusion. These stars are important in several respects. Their progenitors must have had intermediate masses (approximately 5 to 10 $M_\odot$), and they represent a brief and poorly understood phase of late stellar evolution dominated by convection and mass loss. They are among the most significant dust producers in their respective galaxies, returning significant quantities of processed material to the interstellar medium. Intermediate-mass AGB variables, such as these, will be among the most distant individual stars observable with the James Webb Space Telescope (JWST), and are likely to be important probes of their respective populations.

It is not surprising that the four variables that we detected at HST wavelengths, and identified as possible AGB stars, are among the bluest objects, lying in the range $0.17 < [3.6] - [4.5] < 0.76$ in Table 4. 15qa is the bluest ($[3.6] - [4.5] = 0.58$) variable that was not detected by HST; however, its host galaxy is 0.4 mag more distant than that of 14bbc, the reddest object that was detected. Thus the detections, or lack thereof, are consistent with our conclusion that these sources are AGB variables.
The fifth variable that was also detected by HST, but does not appear to be an AGB star, is 15mr. As discussed above, it is more luminous than the AGB variables, and is possibly a red supergiant. However, as discussed by K19 for variables in this part of the period–luminosity relation, it could alternatively be a dust-producing binary system.

One source that lies in a position in the period–luminosity consistent with the AGB variables, but may be something else, is 15mt. Its blue Spitzer colors and very large variation amplitudes are not typical, and alternative explanations should be considered. While we might speculate that its periodicity could be due to orbital motion in a binary, we would expect an IR-luminous binary to be dusty and thus have red colors. We observed only a single cycle of variation, so it remains possible that 15mt is actually a transient. Unfortunately we have insufficient information to be confident one way or the other.

14al is a better candidate for an AGB variable, but its period, estimated to be longer than 2160 days, is poorly defined because of insufficient time coverage. There are only a few pulsating stars known with primary periods above 2000 days. If confirmed as a pulsating AGB star, 14al is potentially very interesting. It may be a candidate super-AGB star, i.e., a star with a progenitor mass of about 10 $M_\odot$ that could become an electron-capture SN (Siess 2007; Doherty et al. 2015, 2017). It is well worth a more detailed study with the JWST.

8. Luminous Irregular Infrared Variables

Several classes of stars may produce irregular, or nonperiodic, variability in the IR. These include LBVs, which may undergo repeated outbursts or eruptive mass-loss events capable of forming copious dust, though the mechanism driving such outbursts is not well understood. In Jencson et al. (2019), we presented discoveries of two such sources, SPIRITS 17pc and SPIRITS 17qm, which underwent multiple, extremely red outbursts over the course of several years, and for which we identified luminous counterparts in archival HST imaging, likely to be LBVs. Dust-forming, colliding-wind WC binaries, like the SPIRITS sources presented in Lau et al. (2021), are in fact periodic, but may be classified as irregular variables under our definition presented in Section 2 if their orbital periods are longer than the available Spitzer coverage. In this section, we discuss the six SPIRITS variables that we classify as irregular, and for which we have HST imaging. Their Spitzer light curves are shown in Figure 13. Table 5 gives details of the Spitzer photometry.
8.1. 14qb

IR variability of SPIRITS 14qb in the actively star-forming galaxy NGC 4631 \( (d \approx 7.3 \text{ Mpc}) \) was discovered at our first two epochs of SPIRITS observations. Comparison of IRAC frames obtained in 2014 March and April, with archival images from 2004, showed that 14qb had risen \(~1.1\) and \(0.8\) mag at 3.6 and 4.5 \(\mu\)m, respectively, as shown in the Spitzer light curve in the top left panel of Figure 13. The source was luminous \( (M_{[4.5]} \approx -14.5 \text{ in 2014 March}) \) and extremely red \( ([3.6] - [4.5] \approx 1.1) \). At our observation a year later, in 2015 March, 14qb had faded about 0.2 mag at both wavelengths, and was still fainter five months later. At that point, we considered it to be a “slow” SPRITE transient, and triggered our HST observations; these were obtained in 2015 November. Since then, however, 14qb did not continue to fade like a transient; instead, it slowly brightened, up to our most recent, and final, Spitzer observations in 2019 October. Thus it cannot be considered to be a SPRITE, nor is it periodic, and we classify 14qb as irregular.

In addition to our triggered HST WFC3 observations in 2015, there are archival frames obtained with ACS in 2004 (GO-9765, PI R. de Jong). We astrometrically registered the ACS \( I\)-band frame with a Spitzer 4.5 \(\mu\)m difference image showing 14qb at maximum brightness. 14qb is located in an extremely crowded star-forming region southwest of the nucleus of NGC 4631, with numerous young stars and dust lanes. Figure 14 shows a color rendition of the location, created in the HLA from ACS frames in \( V \) and \( I \). The vicinity of 14qb exhibits fairly high and spatially variable extinction, and the object lies near the northern edge of a rich young association.

There are a few faint stars within a 3\(\sigma\) astrometric error circle in the HST \( I \) frame, none of which varied significantly from 2004 to 2015. None of these stars are conspicuous in the 2015 \( J \) and \( H \) frames. We conclude that there is no credible counterpart at \( J, J, \) and \( H \) to this bright and very cool IR variable. Based on the limited information available for this source, we cannot conclusively determine its nature. Its high IR luminosity could be consistent with dust formation by an LBV, for example, but the star must be heavily enshrouded to explain the lack of a detectable optical or near-IR counterpart.

8.2. 14akj and 14atl

As noted in the last column of Table 1, SPIRITS 14akj and 14atl are two IR variables that serendipitously lie near the primary HST target 15nz (a periodic variable discussed above in Section 7.1). These two objects belong to the actively star-forming spiral galaxy M83 \( (d \approx 4.7 \text{ Mpc}) \). Their Spitzer light curves are shown in the top middle and top right panels of Figure 13.

We classify both variables as irregular. 14akj slowly and irregularly declined in brightness over the duration of the Spitzer imaging. However, we cannot completely rule out that it might be a periodic variable with a very long period, of the order of \(8\) years. It is extremely red, with a color of \([3.6] - [4.5] \approx 1.1\); it is also luminous, having fallen from \(M_{[4.5]} \approx -14.5 \) to \(-14.0\) from 2008 to 2019. 14atl differs from 14akj in several respects. It slowly rose from 2010 to mid-2018 by about one magnitude, but with two dips in brightness. Our final observations showed that another dip was underway. 14atl is relatively quite “blue,” with \([3.6] - [4.5] \approx 0.15\), and it is less luminous than 14akj, with an absolute magnitude averaging about \(M_{[4.5]} \approx -12.5\) over the final few years of our monitoring.

We astrometrically registered a Spitzer IRAC channel 2 image showing both 14akj and 14atl with an HST/WFC3 \( I\)-band image obtained in 2009 (GO-11360, PI R. O’Connell), in order to determine their locations in the HST frame. The site of 14akj lies in a very active star-forming region. Inside a 3\(\sigma\) error circle there are three fairly bright stars, and several fainter ones, forming a small cluster, as shown in the top two panels of Figure 15. The top left panel shows a false-color rendition of the \( I\)-band image with a 3\(\sigma\) error circle marking the position of 14akj. None of the three bright stars varied significantly between the two available HST \( I\)-band frames (the other being a 2016 image from program GO-14059, PI R. Soria). None of these stars are prominent in the one available \( J \) frame nor the
two archival $H$ frames. The top right panel is a color rendition of the field, obtained from the HLA and created from WFC3 frames obtained in 2016 in $u$, $B$, and $I$. The image shows several rich young stellar associations in the vicinity of 14akj. All of the stars inside the error circle are seen to be quite blue. It could be that the counterpart to 14akj was not detected in the optical or near-IR HST images, in which case it is likely to be a heavily enshrouded, and fairly massive young object. Alternatively, this source could be consistent with a WC colliding-wind binary system, where one of the bright blue stars detected with HST is, in fact, the counterpart. Optical spectroscopy to search for WC features, as presented for other SPIRITS sources in Lau et al. (2021), could test this scenario.

The site of 14atl was also astrometrically localized in the same HST $I$ frame as described above. The bottom two pictures in Figure 15 depict the $I$ frame and the $3\sigma$ location (right panel), and the HLA color rendition (right panel). Inside the error circle is an optically bright star, and the color rendition shows that this object is extremely red. This star is very bright in a single available $J$ frame and two $H$ frames. Between 2009 and 2016 the star brightened in $I$ by about 0.5 mag, and in $H$ by 0.6 mag. These are in accordance with a similar brightening seen in the Spitzer data. There is thus little doubt that this star is the optical and near-IR counterpart of 14atl.

Because the HSC magnitudes are averaged over widely separated epochs, we performed aperture photometry on the available individual WFC3 frames. We used the zero-points and corrections to infinite aperture from the site referenced in footnote 10. Table 6 gives our results. The uncertainties in the magnitudes, including systematics from the camera calibrations, are generally about ±0.02–0.03 mag.

We show the 2009 and 2016 SEDs of 14atl in Figure 16, constructed from our HST aperture photometry of the optical/near-IR counterpart and linear interpolations of the $[3.6]$ and $[4.5]$ magnitudes to the corresponding epochs. The SEDs at both epochs are similar, peaking between $\approx 1$–2 $\mu$m at band luminosities of $\lambda L_\lambda \approx 10^5 L_\odot$. In comparison with PHOENIX...
model photospheres (nonrotating, solar metallicity; Kučinskas et al. 2005, 2006), the SEDs appear consistent with a luminous red supergiant with an effective temperature of $T_{\text{eff}} \approx 3500$ K and bolometric luminosities of $\log L_{\text{bol}}/L_\odot \approx 5.24–5.47$. We note an excess of mid-IR flux at [3.6] and [4.5] compared to the stellar models. Interestingly, the mid-IR color is redder when the star is fainter. Together, these facts likely point to emission from warm dust that condenses in a stellar wind. The observed variability is likely associated with semiregular variations arising from pulsational instabilities, which are common in cool supergiants (e.g., Yoon & Cantiello 2010; Yang & Jiang 2011).

### 8.3. 15ahp

The IR variable SPIRITS 15ahp is another serendipitous target, lying by chance in the field of our HST observations of the periodic variables 15ahg, 14al, and 14dd, which were discussed above (Section 7.3). This field is in the M81-group galaxy NGC 2403, and the site of 15ahp lies in a star-forming spiral arm of the host galaxy. The IR light curves of 15ahp are shown in the bottom left panel of Figure 13. This object varies in IR brightness by about 0.2 mag peak-to-peak, on a fairly short timescale of a few months. We classify it as an irregular variable. Its IR color also appears to vary.

The astrometric registration of Spitzer frames with HST images of this site was described in Section 7.3. The top two panels in Figure 17 show the $3\sigma$ astrometric error circles for the location of 15ahp in two of the three available HST I-band images, an archival one from 2005 (GO-10402, PI R. Chandar), and the other is our frame obtained as a result of our triggered 2016 March 7 observation. A third I-band image from 2019 is available (GO-15645, PI D. Sand) but not illustrated. Inside the error circle is a prominent star, which rose in I-band brightness by about 0.25 mag between 2005 and 2016. This is qualitatively consistent with the brightening at [3.6] and [4.5] over the same interval, as seen in Figure 13. 15ahp then faded by 0.17 mag at the 2019 HST observation. The star is very bright at $J$ and $H$, as shown in the bottom two panels in Figure 17. There is thus little doubt that this object is the optical/near-IR counterpart of SPIRITS 15ahp. The HSC gives magnitudes (AB scale) of this star from the 2005 ACS frames of $F658N = 21.74$ and $I = 20.25$, and from the 2016 WFC3 frames of $I = 20.07, J = 18.63$, and $H = 18.17$.

The multiepoch SED, constructed in a similar manner to that of 14at, is shown in the right panel of Figure 16. As with 14at, the star appears consistent with a red supergiant, though perhaps a bit cooler and less luminous ($T_{\text{eff}} \approx 3300$ K; $\log L_{\text{bol}}/L_\odot \approx 5.1$), based on our comparisons with PHOENIX models. We again note a mid-IR excess compared to the photospheric models and that the mid-IR color is slightly redder when the star is fainter, likely indicating the presence of circumstellar dust.

### 8.4. 14th

SPIRITS 14th is yet another serendipitous target, which happens to lie in the field of 15wt and 14bbc in the nearby galaxy NGC 7793, which we imaged with HST as described above (Section 7.5) on 2016 April 18. The bottom middle panel in Figure 13 shows the Spitzer light curves, which we classify as ones of an irregular variable. 14th brightened by about 1 mag from late 2011 to a peak in early 2014, and then declined by nearly the same amount over the next two years. Since then it has remained nearly constant at [4.5] but somewhat “noisy” at [3.6], with our most recent and final observation showing it quite faint at [3.6]. This variable is extremely red, with a typical color of [3.6] – [4.5] $\approx 1.5$. It is not extremely luminous; the absolute magnitude at our final observation was about $M_{[4.5]} \approx -11.5$.
We registered a Spitzer frame showing 14th near maximum brightness with HST I-band images, as discussed for 15wt and 14bbc in Section 7.5. The site is in a very rich star field. There are a few resolved stars within a 3σ registration error circle, on top of an unresolved or partially resolved background. Comparing I frames obtained in 2003, 2014, 2016 (our triggered observation), and 2017 shows no significant variations of any of these stars. Moreover, none of them are conspicuous at J and H, nor varied between JH images obtained in 2016 and 2018. We conclude that 14th is undetected in the optical and near-IR HST images, which is consistent with its extremely red IR color. Again, without an obvious counterpart detection in the optical or near-IR, it is difficult to draw strong conclusions about the nature of the source, other than that it is likely a young, fairly massive, and heavily enshrouded object.

8.5. 16aj

SPIRITS 16aj was announced as a possible transient by Jencson et al. (2016b). It lies in the actively star-forming barred spiral NGC 2903, the most distant of the galaxies discussed in this paper (d ≃ 9.2 Mpc). The Spitzer light curves of 16aj are shown in the bottom right panel of Figure 13. This object rose in brightness by about 1 mag over the first two years of SPIRITS monitoring (early 2014 to early 2016), leading us to consider it a slow SPRITE; at that point we triggered HST imaging of the site, which was obtained on 2016 May 23. However, since early 2016 the object has remained at a nearly constant magnitude, although with possible short-term variations of a few tenths of a magnitude. Thus we now classify 16aj as an irregular variable, rather than a true transient. It is fairly red ([3.6] − [4.5] ≃ 0.9) and of relatively high luminosity (M_{[4.5]} ≃ −13.9).

We astrometrically registered Spitzer frames, including a difference image showing 16aj, with an HST ACS I-band image taken in 2004 (GO-9788, PI L. Ho) and with our own I frame obtained in 2016. At the site there are a few resolved faint stars, lying on a sheet of unresolved starlight. We see no I-band variations between 2004 and 2016, and the J and H frames we obtained on the same date in 2016 reveal no extremely red stars. The site lies on the edge of a rich young association and HII region, and there are numerous dark dust lanes in the vicinity. We conclude that 16aj lacks a detectable optical or near-IR counterpart. Similarly to 14qb and 14th, we conclude only that the star is likely to be relatively young, massive, and heavily enshrouded.

9. Summary

SPIRITS was the first large-scale monitoring survey of nearby galaxies, using the warm Spitzer telescope to search for luminous variable stars and transients at IR wavelengths. In the work described here, we employed new and archival optical and near-IR HST images to study the sites of 21 SPIRITS variables. The selected targets were of special interest because they were undetected or very faint in ground-based optical surveys. Our aims were to search for progenitors, attempt to detect the sources during outburst using deep HST imaging, and characterize their environments.

We classify the SPIRITS variables into three groups based on their photometric behavior: SPRITEs and transients; periodic variables; and irregular variables. Our main results from the HST imaging are as follows.
1. SPRITEs are a new class of intermediate-luminosity IR transients that lack counterparts in deep ground-based optical imaging. They are defined as objects having absolute magnitudes at maximum in the range $-14 < M_{\text{IR}} < -11$. We investigated HST images of three SPRITEs, two of them with fast outburst timescales of a few days to a few weeks, and one with a slow timescale of nearly three years. Like most SPRITEs, two of the three occurred in dusty, star-forming regions, consistent with an origin from massive stars. No progenitors were found in deep preoutburst archival HST images for the two objects in young regions. We did detect one of them—the slowly evolving $17\text{fe}$—during outburst at $J$ and $H$. This allowed us to construct an SED, indicating that $17\text{fe}$ during eruption was a dusty object with a temperature of about 1050 K. Unusually, the third SPRITE candidate, the very fast $14\text{axa}$, occurred in the old bulge of M81 rather than in a star-forming region. It appears to have been a dusty classical nova. Some, or many, of the fast SPRITEs at the low end of the luminosity range are likely to be classical novae, instead of arising from massive stars. Most SPRITEs, however, are events of an uncertain nature—possibly a mixture of massive stellar mergers, dust-obscured core-collapse supernovae, and eruptions of massive stars related to those of luminous blue variables.

2. Variable stars are much more conspicuous among the brightest members of stellar populations in the IR than they are in the optical, particularly in late-type galaxies. More than half of our SPIRITS targets, although initially considered to be transients, proved to be periodic variables. Their pulsation periods are long, ranging from $\sim 670$ to over 2100 days. These objects are likely to be highly evolved, dusty AGB stars, similar to OH/IR objects known in the Galaxy and Magellanic Clouds. The pulsators found by SPIRITS are strongly associated with star-forming regions in nearby spirals and irregular galaxies, and they likely arise from intermediate-mass stars ($\sim 5$–$10 \text{ M}_{\odot}$). Out of the 12 periodic variables for which we have HST images, only five were warm enough to be detected with HST at $I$, $J$, and/or $H$, along with one uncertain case.

3. Six SPIRITS variables did not fit our definitions for transients or (likely) periodic variables, and we classify them as irregular. Two of these sources, $14\text{at}$ and $15\text{ah}$, had relatively blue IR colors ($-0.1 \lesssim [3.6] - [4.5] \lesssim 0.2$) and had bright, red counterparts in HST imaging. Their optical–near-IR SEDs are consistent with those of luminous, pulsating red supergiants. The remaining four irregular variables are much redder at IR wavelengths ($[3.6] - [4.5] \gtrsim 0.9$) and, not surprisingly, we did not identify convincing optical or near-IR counterparts in deep HST images. These objects may be consistent with eruptive, dust-forming mass-loss events, like those of LBVs, but their massive stellar counterparts are likely heavily enshrouded. For the case of $14\text{akj}$, however, we noted a possible association with several luminous blue stars. $14\text{akj}$ could therefore instead correspond to a dust-forming colliding-wind WC-type binary. Optical spectroscopy to search for prominent WC emission features would test this possibility.

4. None of the SPIRITS transients observed by HST appear to be flares associated with YSOs. Although some lie in the dust lanes of the host galaxies, none of the investigated transients are directly associated with star-forming complexes. However, future IR observations with facilities such as the JWST and the Nancy Roman Space Telescope may reveal YSO transients in star-forming regions.

The SPIRITS project was the first systematic time-domain reconnaissance of stellar variability among IR-luminous stars in nearby galaxies. It revealed several new classes of extremely cool and dusty transients and pulsating or irregular variables. An understanding of the nature of these diverse objects will require more intensive time coverage of their variations and outbursts than was possible with Spitzer. Infrared spectroscopy would be a key new element in such investigations. Considerable progress will be possible with the powerful IR capabilities of the JWST and the Roman Space Telescope.

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ORCID iDs

Howard E. Bond @ https://orcid.org/0000-0003-1377-7145
Jacob E. Jencson @ https://orcid.org/0000-0001-5754-4007
Patricia A. Whitelock @ https://orcid.org/0000-0002-4678-4432
Scott M. Adams @ https://orcid.org/0000-0001-5855-5939
John Bally @ https://orcid.org/0000-0001-8135-6612
Ann Marie Cody @ https://orcid.org/0000-0002-3656-6706
Robert D. Gehrz @ https://orcid.org/0000-0003-1319-4089
Mansi M. Kasliwal @ https://orcid.org/0000-0002-5619-4938
Frank J. Masci @ https://orcid.org/0000-0002-8532-9395

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