Late-onset Circumstellar Medium Interactions are Rare: An Unbiased GALEX View of Type Ia Supernovae

Liam O. Dubay\textsuperscript{1,2,3,5} \textsuperscript{©}, Michael A. Tucker\textsuperscript{3,6} \textsuperscript{©}, Aaron Do\textsuperscript{3} \textsuperscript{©}, Benjamin J. Shappee\textsuperscript{3} \textsuperscript{©}, and Gagandeep S. Anand\textsuperscript{3,4} \textsuperscript{©}, Benjamin J. Shappee\textsuperscript{3} \textsuperscript{©}, and Gagandeep S. Anand\textsuperscript{3,4} \textsuperscript{©}

\textsuperscript{1}Department of Astronomy, The Ohio State University, 140 West 18th Avenue, Columbus, OH 43210, USA; liam.dubay@gmail.com
\textsuperscript{2}Institute for Astronomy, University of Hawai‘i, 2680 Woodlawn Drive, Honolulu, HI 96822, USA
\textsuperscript{3}Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA

Received 2021 April 5; revised 2021 November 3; accepted 2021 November 18; published 2022 February 16

Abstract

Using ultraviolet (UV) light curves, we constrain the circumstellar environments of 1080 Type Ia supernovae (SNe Ia) within z < 0.5 from archival Galaxy Evolution Explorer (GALEX) observations. All SNe Ia are required to have pre- and post-explosion GALEX observations to ensure adequate subtraction of the host-galaxy flux. Using the late-time GALEX observations, we look for the UV excess expected from any interaction between the SN ejecta and circumstellar material (CSM). Four SNe Ia are detected near maximum light, and we compare the GALEX photometry to archival data. However, we find that none of our targets show convincing evidence of CSM interaction. A recent Hubble Space Telescope (HST) survey estimates that ~6\% of SNe Ia may interact with distant CSM, but statistical inferences are complicated by the small sample size and selection effects. By injecting model light curves into our data and then recovering them, we constrain a broad range of CSM interactions based on the CSM interaction start time and the maximum luminosity. Combining our GALEX nondetections with the HST results, we constrain occurrence of late-onset CSM interaction among SNe Ia with moderate CSM interaction, similar to that observed in PTF11kx, to f_{\text{CSM}} \lesssim 5.1\% between 0 and 500 days after discovery and \lesssim 2.7\% between 500 and 1000 days after discovery at 90\% confidence. For weaker CSM interactions similar to SN 2015cp, we obtain limits of \lesssim 16\% and \lesssim 4.8\%, respectively, for the same time ranges.

Unified Astronomy Thesaurus concepts: Type Ia supernovae (1728); Circumstellar matter (241)

Supporting material: machine-readable tables

1. Introduction

Type Ia supernovae (SNe Ia) are thermonuclear explosions of carbon–oxygen white dwarf stars (C/O WDs; Hoyle & Fowler 1960), and are typically classified based on the lack of H and He emission and the presence of strong Si II absorption in their spectra (Filippenko 1997). SNe Ia are important for many fields of astrophysics: they are useful as standardizable candles (Phillips 1993), and they played a leading role in the discovery of dark energy (Riess et al. 1998; Perlmutter et al. 1999). SNe Ia also influence the chemical evolution and distribution of metals in the universe (e.g., Greggio & Renzini 1983; Wiersma et al. 2011). However, the nature of their progenitor systems is not fully understood. In particular, there is an ongoing debate about the relative contributions from the single degenerate (SD) and double degenerate (DD) channels (for reviews, see Maoz et al. 2014; Livio & Mazzali 2018; Ruiter 2020). The existence of multiple channels for producing SNe Ia could lead to systematic errors in SN Ia-calibrated distances if the relative contributions evolve with cosmic time (e.g., D’Andrea et al. 2011; Howell 2011).

In the DD scenario, two WDs merge after an inspiral from a tight binary (Iben & Tutukov 1984; Webbink 1984; Pakmor et al. 2012) or a head-on collision (Benz et al. 1989; Thompson 2011). The theoretical rate of WD mergers is consistent with the observed rate of SNe Ia (e.g., Yungelson et al. 1994; Ruiter et al. 2009), and the lack of H and He emission in the spectra of normal SNe Ia is easily explained by the DD model. However, DD progenitor systems are difficult to detect even within the Milky Way (Rebassa-Mansergas et al. 2019), and the merger of two WDs may result in a high-mass WD or neutron star rather than a thermonuclear explosion (Nomoto & Iben 1985; Saio & Nomoto 1998; Shen et al. 2012). Despite these issues, in recent years the DD scenario has become the leading model for most SN Ia progenitors.

Conversely, an SD system consists of a WD and a close nondegenerate companion, such as a red giant, helium star, or main-sequence star (Whelan & Iben 1973; Nomoto 1982; Yoon & Langer 2003). In most models, the WD accretes matter from its companion and explodes once it nears the Chandrasekhar mass (Whelan & Iben 1973). Because the explosion only occurs when the WD reaches its maximum mass, the SD model can readily account for the homogeneity of normal SNe Ia. However, the presence of a close nondegenerate companion should produce observable signatures such as photometric irregularities in the early light curve as the ejecta impact the companion star (e.g., Kasen 2010; Boehner et al. 2017), emission lines in nebular-phase spectra produced by material stripped from the donor star (e.g., Wheeler et al. 1975; Marietta et al. 2000; Pan et al. 2012), and radio emission from interaction with material carried by the stellar wind (e.g., Chevalier 1982a, 1982b). Recent searches for these observational signatures have not found any conclusive evidence of an SD progenitor system (e.g., Panagia et al. 2006; Chomiuk et al. 2012).
Tycho G has been proposed as the surviving companion of SN 1572, also known as Tycho’s SN (e.g., Ruiz-Lapuente et al. 2004) and is supported by a recent kinematic study (Ruiz-Lapuente et al. 2019), but Shappee et al. (2013a) argue the star is not luminous enough. Other searches for surviving nondegenerate companions have come up short (e.g., Schaefer & Pagnotta 2012; Do et al. 2021).

While some or even most SNe Ia may result from the DD channel, some peculiar SNe Ia are more consistent with a SD progenitor system. One such subset of SNe Ia are those with evidence for a dense circumstellar medium (CSM) in close proximity to the explosion. These events, termed “SNe Ia-CSM,” are often more luminous and feature stronger H emission lines (Silverman et al. 2013a). The first two members of this class were SN 2002ic (Hamuy et al. 2003; Deng et al. 2004; Kotak et al. 2004; Wang et al. 2004; Wood-Vasey et al. 2004) and SN 2005gj (Aldering et al. 2006; Prieto et al. 2007). While some have argued that a core-collapse progenitor better explains these events (Benetti et al. 2006; Trundle et al. 2008), Fox et al. (2015) found that late-time spectra of SNe Ia-CSM are more consistent with a thermonuclear explosion. PTF11kx was the first unambiguous case of an SN Ia interacting with a dense CSM (Dilday et al. 2012; Silverman et al. 2013b), and since its discovery, the list of unambiguous SNe Ia-CSM has steadily grown (e.g., Silverman et al. 2013a; Yao et al. 2019; Graham et al. 2019b; Srivastav et al. 2021).

The presence and strength of CSM interaction can constrain the SN Ia progenitor system. A DD collision involving two C/O WDs may produce CSM, but with such a small H mass fraction ($M_H/M_{WD} \lesssim 10^{-4}$; Romero et al. 2012) the amount of hydrogen ejected would be negligible. A He + C/O WD system is expected to eject $3-6 \times 10^{-5} M_\odot$ prior to the merger (Shen et al. 2013), which is likely too little mass to explain the H$\alpha$ emission observed in SNe Ia-CSM. By contrast, the mass-transfer process in the SD scenario is inefficient and may produce up to several $M_\odot$ of H-rich CSM as material expelled by the companion (e.g., by wind from a red giant) is swept up by a nova eruption to produce a dense circumstellar shell (e.g., Hamuy et al. 2003; Walder et al. 2008; Moore & Bildsten 2012). Symbiotic progenitor systems in particular are expected to have a mass-loss rate of $M \gtrsim 1.7 \times 10^{-4} M_\odot$ yr$^{-1}$, assuming wind velocity $v_w \sim 100$ km s$^{-1}$ (Hachisu et al. 1999; Lundkvist et al. 2020). Aldering et al. (2006) estimate a mass of $\gtrsim 10^{-2} M_\odot$ would be necessary to explain the observed H$\alpha$ luminosity of SN 2005gj. While the SD scenario has trouble accounting for the lack of nebular H$\alpha$ emission in most SNe Ia (e.g., Leonard 2007; Shappee et al. 2013b, 2018; Tucker et al. 2020), it is a promising progenitor channel for SNe Ia-CSM (Silverman et al. 2013a).

Most SNe Ia-CSM are discovered before or near maximum light and show evidence of CSM interaction within days of peak SN brightness. For example, a strong H$\alpha$ line was present in the spectrum of SN 2002ic at +6 days past maximum light (Hamuy et al. 2003), and H$\alpha$ was visible in SN 2005gj before peak brightness (Aldering et al. 2006). However, a handful of SNe Ia-CSM have recently been discovered where there is a clear lack of CSM interaction in early observations, with the H$\alpha$ emission appearing weeks or months later. The first example of a late-onset SN Ia-CSM was PTF11kx, which featured prominent H and Ca emission starting 59 days after explosion (Dilday et al. 2012) and persisting after +3.5 yr (Silverman et al. 2013b; Graham et al. 2017). Additionally, time-variable Na absorption has been linked to the presence of CSM (Sternberg et al. 2011) and may indicate an unusual geometry of the CSM (Simon et al. 2009), which could also be associated with time-variable H$\alpha$ emission. Dilday et al. (2012) propose that PTF11kx resulted from a symbiotic nova progenitor, though Soker et al. (2013) offer an alternative explanation in the violent prompt merger scenario.

There is reason to expect that CSM interaction may begin even later in other SNe Ia. CSM shells generated by recurrent novae may reach $\sim 10^{17}$ cm by the time of the next eruption (Moore & Bildsten 2012). At this distance, ejecta traveling at $\sim 23000$ km s$^{-1}$ (e.g., Garavini et al. 2005) would not begin to interact for $\sim 500$ days. Even current radio observations do not provide meaningful constraints on distant CSM shells (Harris et al. 2021). If CSM is often present at such a large distance from the WD, then typical SN observations might systematically miss its signatures, as they usually continue for only a few months after the explosion (e.g., Hicken et al. 2012). Intrinsic differences may also exist among the SNe Ia-CSM class itself. Most SNe Ia-CSM occur in star-forming host galaxies, exhibit H$\alpha$ luminosities of $L_{H\alpha} \approx 10^{46}$ erg s$^{-1}$, and have bright, slowly evolving light curves (Silverman et al. 2013a). ASASSN-18tb/SN 2018fhw was the first subluminous, fast-declining SN Ia observed to have H$\alpha$ emission after maximum light (Kollmeier et al. 2019; Valley et al. 2019). ATLAS18qtd/SN 2018eqq, another low-luminosity and fast-declining event, showed H$\alpha$ emission in spectra taken at +193 and +307 days after peak (Prieto et al. 2020). The H$\alpha$ luminosity observed in ASASSN-18tb and ATLAS18qtd was much lower than in other known SNe Ia-CSM and was inconsistent with both material stripped from a companion in an SD system (Marietta et al. 2000; Liu et al. 2012; Bohner et al. 2017) and typical SNe Ia-CSM (Tucker & Shappee 2020). This complicates our understanding of SNe Ia-CSM, as it is unclear whether these objects represent the extreme end of a continuous distribution or constitute a new class of thermonuclear explosions.

While SNe Ia are predominantly optical phenomena (Filippenko 1997; Brown et al. 2010), CSM interaction produces ultraviolet (UV) emission that distinguishes these events from both the underlying emission from the ejecta and their host galaxy (e.g., SN 2005gj; Immler et al. 2005). To search for late-onset CSM interaction, defined as $\geq 100$ days after peak brightness, Graham et al. (2019b) performed a Hubble Space Telescope (HST) near-ultraviolet (NUV) snapshot survey targeting 72 nearby SNe Ia 1–3 yr after explosion. ASASSN-15og showed early signs of CSM interaction (Monroe et al. 2015; Holoien et al. 2017a) and was detected in the NUV at +477 days after maximum light (Graham et al. 2019b). Graham et al. (2019b) also detected NUV emission in SN 2015cp at +664 days. SN 2015cp was originally classified as an SN Ia-91T, and showed no signs of CSM interaction in its spectrum at +45 days (Frohmaier et al. 2016), but subsequent spectra taken between +694 and +785 days revealed declining H$\alpha$ and Ca II emission consistent with interaction between the SN ejecta and a distant shell of H-rich CSM (Graham et al. 2019b). This discovery demonstrates that late-onset SNe Ia-CSM may be missed in typical SN observations.

SNe Ia-CSM are rare (Silverman et al. 2013a; Graham et al. 2019b), but the true occurrence rate is not well-constrained.
Graham et al. (2019b) estimated that the fraction of their targets that have CSM within $r_{\text{CSM}} \approx 3 \times 10^{17}$ cm is $f_{\text{CSM}} \approx 6\%$. However, they selected targets with characteristics typical of SNe Ia-CSM, such as an SN 1991T–like spectrum (e.g., Phillips et al. 1992), high photospheric velocity, a blueshifted Na I D absorption line, or a host with a young stellar population. Therefore, their sample is already biased toward finding SNe Ia-CSM.

To better constrain the fraction of SNe Ia with late-onset CSM interaction, we search for UV emission from known SNe Ia in archival data from the Galaxy Evolution Explorer spacecraft (GALEX; Martin et al. 2005). In Section 2, we describe our target selection and GALEX observations. In Section 3, we present detections of normal SNe Ia and convert nondetections to limits on intrinsic UV luminosity. In Section 4, we constrain the occurrence rate of late-onset SNe Ia-CSM. We present our conclusions in Section 5. Throughout this work, we adopt $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.3$, and $\Omega_\Lambda = 0.7$. We present all observation times in terms of days after discovery in the SN rest frame.

2. Observations and Target Selection

We obtained GALEX (Martin et al. 2005) UV light curves of 1080 SNe Ia to search for signatures of SN Ia ejecta interacting with nearby CSM. GALEX was a NASA Small Explorer telescope that surveyed the entire sky in the UV from 2003 to 2013, and its data are publicly available at the Mikulski Archive for Space Telescopes (MAST). GALEX is particularly suited for this purpose due to the low background noise of its photon-counting detectors (Martin et al. 2005) and the low surface brightness of SN Ia host galaxies in the UV (e.g., Gil de Paz et al. 2007). Previous studies have searched for UV emission from Type II SNe in GALEX data (e.g., Gal-Yam et al. 2008; Gezari et al. 2008, 2010, 2015; Ganot et al. 2016; Soumagnac et al. 2019; Ganot et al. 2020), but it has not yet been used for a large study of SNe Ia.

In Section 2.1, we briefly describe the GALEX spacecraft. In Section 2.2, we describe the data pipeline, and we address the photometric precision and stability of GALEX. In Section 2.3, we describe our selection of a Type Ia sample. In Section 2.4, we discuss very nearby ($z < 0.01$) SNe Ia without pre-explosion imaging. We discuss our host-galaxy subtraction process in Section 2.5.

2.1. Survey Configuration

GALEX operated in low-Earth orbit with a 50 cm objective and a 1°2 circular field of view (Martin et al. 2005). It obtained simultaneous images in the FUV (1340–1800 Å) and NUV (1700–3000 Å) bands until the FUV detector failed in 2009, after which the NUV detector operated alone until the end of the mission in 2013. GALEX performed several imaging surveys during its decade of operation, including the All-Sky Imaging Survey (AIS), the Medium Imaging Survey (MIS), the Deep Imaging Survey (DIS), and the Nearby Galaxies Survey (NGS; Martin et al. 2005, see their Table 2). The spacecraft covered nearly 77% of the sky over its ten-year lifetime in at least one band (Million et al. 2016) to a sensitivity of $\geq 20.5$ AB magnitudes (Martin et al. 2005).

Figure 1 compares the GALEX NUV and FUV filters to the HST F275W filter and the Swift/UVOT filters. Filter response curves were provided by the Spanish Virtual Observatory (SVO) Filter Profile Service (Rodrigo et al. 2012; Rodrigo & Solano 2020). The GALEX NUV filter has an effective wavelength $\lambda_{\text{eff}} = 2305$ Å and an equivalent width $W_{\text{eff}} = 770$ Å, which is similar to—but slightly wider than—the Swift UVM2 filter. The NUV filter is bluer and wider than the HST F275W filter utilized by Graham et al. (2019b) in their search for SNe Ia-CSM. The GALEX FUV filter, with $\lambda_{\text{eff}} = 1550$ Å and $W_{\text{eff}} = 265$ Å, has no direct Swift counterpart, covering shorter wavelengths than any of the UVOT filters.

2.2. Data Reduction and GPHOTON Photometry

We use the GPHOTON package version 1.28.9 (Million et al. 2016) to query GALEX data products for our targets. No coadding is implemented to maximize temporal coverage, so single-epoch exposure times range from $\sim 100$–1500 s. Million et al. (2016) found the relative astrometry between source positions in the GALEX Merged Catalog (MCAT) and centers-of-brightness determined by GAPERTURE to be better than 0.01″, so we do not further correct the GALEX astrometry.

Light curves are queried with an aperture radius of 6″, equivalent to the APER4 value in MCAT, and a background estimation annulus from 10″ to 15″. Choosing an aperture slightly larger than the image FWHM of 5″.5 is a good compromise between capturing flux in the extended wings of the PSF and preventing background sources from contaminating the photometry (Morrissette et al. 2007). We use the background flux computed from the GPHOTON background annulus instead of the MCAT-derived values, as the latter requires a nearby MCAT source for each observation to estimate the background flux. For some short GALEX exposures or faint SN Ia host galaxies no MCAT entries are available, resulting in undefined background flux levels. Using the aperture photometry method allows us to carry out a homogeneous analysis of our full sample.

GPHOTON produces quality flags for the output light curve in several situations. Some flags are generated as “warnings,” whereas some flags are considered “fatal” and the photometry should not be trusted. Fatal flags include “(bkgd) mask edge,” “(extime,) “nonlinearity,” and “spacecraft recovery.” We exclude all light-curve data with these fatal flags and refer the reader to the GPHOTON documentation8 for their descriptions.

The “detector response” flag is the most common flag, affecting ~25% of the GALEX data. This flag is set if any photon event falls outside $\geq 0$.5 from the center of the detector at any point in the exposure. We find the photometry does not show a significant deviation from the MCAT magnitudes until $\geq 0$.6 from the detector center. To improve our photometric completeness, we include photometry within 0″.6 from the detector center, increasing the effective area of the GALEX detector by ~45% compared to the nominal cut at 0″.5. A full description of our photometric testing and validation is provided in Appendix B.

All photometry is corrected for foreground Milky Way extinction using the dust maps of Schlafly & Finkbeiner (2011) and a Cardelli et al. (1989) reddening law. This results in total-

---

8 https://gphotons.readthedocs.io/en/latest/

---

https://archive.stsci.edu/
to-selective extinction values of $R_{\text{NUV}} = 7.95$ and $R_{\text{FUV}} = 8.06$ (see Table 2 from Bianchi 2011), although we caution that Yuan et al. (2013) find a lower $R_{\text{FUV}} \approx 4.5$ but a similar $R_{\text{NUV}}$. We assume the $R_{\text{FUV}}$ value from Bianchi (2011) but note that the vast majority of SNe Ia are away from the Galactic plane and have little Galactic reddening, reducing the consequences of any discrepancy on $R_{\text{FUV}}$.

2.3. Target Selection

We query the Open Supernova Catalog9 (OSC; Guillochon et al. 2017) for objects classified as “SN Ia” and discovered prior to 2014 (as GALEX was decommissioned in June 2013), returning 7265 objects. Several cuts are applied to the sample, to reduce the number of non-SNe Ia objects contaminating our sample, prioritizing purity over completeness. Any objects with disputed classifications in the OSC (i.e., “SN Ia, SN Ib/c”) are removed. Spectroscopic classification is considered robust, so any objects with only an “SN Ia” designation (or variant thereof, e.g., “Ia-91T-like”) and at least one publicly available spectrum are included in our sample. For objects designated “SN Ia” without a publicly available spectrum, we cross-match the SN Ia names with archival International Astronomical Union Circulars, Central Bureau Electronic Telegrams (CBETs), and Astronomer’s Telegrams to search for classification reports without publicly released spectra.

Finally, we include photometrically classified SN Ia from major photometric surveys including the Sloan Digital Sky Survey (SDSS; York et al. 2000) supernova survey (Sako et al. 2008, 2011, 2018), the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS; Chambers et al. 2016; Jones et al. 2017, 2018), the SuperNova Legacy Survey (SNLS; Guy et al. 2010; Conley et al. 2011; Sullivan et al. 2011), and the ESSENCE supernova survey (Miknaitis et al. 2007; Wood-Vasey et al. 2007; Narayan et al. 2016). Photometrically classified SNe Ia are required to have $P_{\text{Ia}} \geq 0.99$, where $P_{\text{Ia}}$ is the probability the transient is a SN Ia (see, e.g., Sako et al. 2011). If multiple surveys observed and classified the same object, we use the highest reported $P_{\text{Ia}}$ value. This probability is used only to determine which SNe Ia to include in our sample, and is not used to weight our results.

Additional cuts are applied to ensure the GALEX observations are of sufficient coverage and depth. A cut of $z \leq 0.5$ is applied to ensure detectable emission, as a GALEX single-visit limiting magnitude of $\sim 22.5$ mag corresponds to an absolute magnitude of $\sim -19.5$ mag at $z = 0.5$. Additionally, all SNe Ia are required to have pre- and post-discovery GALEX observations, to ensure adequate host-galaxy subtraction. As Figure 2 shows, 2248 SNe Ia were observed by GALEX both before and after discovery ($t_{\text{disc}}$), of which all had NUV data and 1648 also had FUV coverage.

SNe Ia with sufficient GALEX coverage and $z \leq 0.5$ are cross-matched with galaxies in the NASA/IPAC Extragalactic Database (NED)10 in order to check for more precise redshifts. SNe Ia with insufficient redshift precision are discussed in Appendix A. We require a projected distance of $< 100$ kpc between the SN Ia location and the center of the host galaxy, to prevent spurious matches and flag SNe Ia with projected offsets of $> 30$ kpc for manual review. Figure 3 shows the final distribution of redshifts in our sample of 1080 SNe Ia.

We also obtain high-precision values for redshift-derived distance and Milky Way extinction from NED. To account for the effect of galactic peculiar velocity, we add an additional systematic distance error of $300 \text{ km s}^{-1}/H_0$ (Zaroubi 2002; Karachentsev et al. 2006) to the uncertainty in the redshift-derived distance estimates. Finally, we incorporate high-quality redshift-independent distances from the Cosmicflows-3 catalog (Tully et al. 2016) where available. Table 1 presents a subset of our sample.

---

9 https://sne.space/

10 https://ned.ipac.caltech.edu/
2.4. Nearby, Historical SNe Ia

There are a number of SNe Ia that were discovered before GALEX launched and have extensive post-discovery coverage. We identify 104 SNe Ia with $z < 0.1$ that were observed by GALEX only after discovery. Of these, 13 SNe Ia had at least 10 epochs in at least one band. We provide a list of these targets in Table 2.

Visual inspection of the GALEX light curves reveals no obvious excess flux after the near-peak epoch ($t_{\text{disc}} < 50$ days). At a distance of 10 Mpc, GALEX should be sensitive down to an absolute magnitude of $M_{\text{UV}} \sim -7.5$ mag, and at 20 Mpc it should be sensitive down to $M_{\text{UV}} \sim -9$ mag. Typical SNe Ia-CSM have peak absolute magnitudes of $-21.3 \leq M_R \leq -19$ mag (Silverman et al. 2013), and Graham et al. (2019b) detected NUV emission from SN 2015cp at $M_{\text{IU2SW}} = -13.1$ mag hundreds of days after peak brightness. While these nearby, historical SNe Ia have high-quality limits from GALEX, we exclude them from our statistical analysis because they lack pre-explosion imaging necessary for host-galaxy subtraction.

2.5. Host-galaxy Subtraction

Our sources are restricted to SNe Ia with GALEX observations both before and after discovery, to ensure adequate subtraction of the host-galaxy flux. This eliminates $\sim 3900$ SNe Ia with only pre- or post-explosion GALEX observations. Normal SNe Ia have a $B$-band rise time between explosion and maximum brightness of $\sim 16$–$25$ days (Ganeshalingam et al. 2011; Firth et al. 2015), while SNe Ia-CSM have somewhat longer rise times in the range of $\sim 20$–$40$ days (Silverman et al. 2013). The OSC only reports the discovery date, so we use $t_0 = t_{\text{disc}} - 50$ days as a conservative estimate for the date of explosion, to avoid including any SN flux in our background measurements.

We use two methods to estimate the host galaxy flux, depending on the number of pre-SN observations available. For SNe Ia with $\geq 5$ GALEX observations prior to discovery, we compute the weighted average of all single-epoch pre-discovery fluxes and use the weighted standard deviation to estimate the associated uncertainty. We expand the formal statistical uncertainty by adding a systematic error contribution in quadrature until the fit has a $\chi^2$ per degree of freedom of unity, and then use these revised uncertainties to compute the uncertainty in the mean.

When there are $< 5$ GALEX observations prior to the SN discovery date in a given filter, it is more difficult to empirically calibrate the uncertainties. If there are multiple pre-discovery observations, we compute the weighted mean and standard deviation of the single-epoch fluxes similarly to the process described above. Then, we include an additional magnitude-dependent systematic uncertainty in quadrature, which is described in Appendix C. After computing the host-galaxy flux and associated uncertainty, the host-galaxy fluxes are subtracted from the post-discovery GALEX observations.

3. Photometric Analysis

We flag targets for review if the host-subtracted light curve has at least one detection at $\geq 5\sigma$ significance or at least three detections at $\geq 3\sigma$ significance. Out of the 1080 SNe Ia in our sample, 10 are flagged for review. One is detected in just the FUV band, and the rest have only NUV detections. We reject three candidates with faint host galaxies, because the uncertainties in the host flux appear to be underestimated. All have few (2–3) host measurements with low signal-to-noise ratios. For $3\sigma$ significance and assuming Gaussian-distributed uncertainties, we expect 1–2 host galaxies to have underestimated host-galaxy fluxes, which is consistent with the three false positives flagged by our search algorithm. A fourth candidate is rejected because the flagged image frame showed significant ghost artifacts. We eliminate a fifth candidate that appears to have an underestimated background flux, because the five epochs within $\pm 3$ days of the flagged frame are not significantly above the host-galaxy and no obvious source is visible in the flagged image frame. One other candidate, ESSENCEn263, has UV detections consistent with the center of the host galaxies and is likely an AGN flare, which we discuss in Appendix D.

3.1. Detections of Normal SNe Ia

The four remaining candidates, all detected in the NUV, are detections of normal SNe Ia near maximum light. Figure 4 shows the near-peak light curves of SN 2007on (see Pollas & Klotz 2007), SN 2008hv (Pignata et al. 2008), SN 2009gf (Nakano 2009), and SN 2010ai (Caldwell 2010). The GALEX NUV light curves for SNe 2007on, 2008hv, and 2009gf are consistent with the Swift UV light curves from Brown et al. (2014). There are no UV observations of SN 2010ai in the literature, so we present its GALEX NUV light curve alongside optical measurements by Hicken et al. (2012). For all photometric data, we assume a monochromatic flux density as in the AB magnitude system (Oke & Gunn 1983).

We can also constrain the near-peak FUV flux for SN 2007on and SN 2008hv. For SN 2007on, we constrain its FUV emission at $t_{\text{disc}} + 12$ rest-frame days to be $< 2.2 \times 10^{36}$ erg s$^{-1}$ Å$^{-1}$ at $3\sigma$ confidence, or $\leq 3\%$ of the NUV emission at that epoch. For SN 2008hv, we constrain its FUV emission at $t_{\text{disc}} + 39$ days to be $< 1.68 \times 10^{37}$ erg s$^{-1}$ Å$^{-1}$, or $\leq 78\%$ of the NUV emission at that epoch. Sauer et al. (2008) found that the flux at 1500 Å should be an order of magnitude lower than at 2250 Å in their model of the UV spectrum for SN 2001ep (see their Figure 4). Our nondetections in the FUV are qualitatively consistent with this model.

None of the four near-peak SNe Ia are candidates for CSM interaction. SN 2007on has been identified as a “transitional” SN Ia, in between the SN 1991bg and normal classes of SNe Ia (Gall et al. 2018), and it shows no signatures of CSM in its.

Figure 3. The redshift distribution of the 1080 SNe Ia.
| Target Name | Disc. Date | R.A. (h:m:s) | Decl. (d:m:s) | Obs. \( t_{\text{last}} \)\(^{b}\) | \( t_{\text{last}} \)\(^{c}\) | \( t_{\text{last}} \)\(^{d}\) | Redshift | Distance (Mpc) | \( A_V \)\(^{e}\) | Reference(s) |
|-------------|------------|-------------|---------------|----------------|----------------|----------------|-----------|----------------|-------------|-------------|
| ESSENCEg097 | 2004-10-05 | 23: 27: 37.16 | – 09: 35: 21 | 23 | –407 | 2181 | 357 | 0.343 | 1464 ± 103 | 0.086 | Miknaitis et al. (2007) |
| ESSENCEg142 | 2004-10-09 | 23: 28: 37.7 | – 08: 45: 04 | 16 | –35 | 2177 | 353 | 0.404 | 1725 ± 121 | 0.078 | Miknaitis et al. (2007) |
| ESSENCEg230 | 2004-10-17 | 01: 11: 56.31 | + 00: 07: 27.7 | 19 | –376 | 2532 | 1081 | 0.392 | 1674 ± 117 | 0.084 | Miknaitis et al. (2007) |
| ESSENCEm027 | 2005-09-26 | 01: 09: 15.01 | + 00: 08: 14.8 | 14 | –720 | 1870 | 742 | 0.289 | 1233 ± 86 | 0.078 | Miknaitis et al. (2007) |
| ESSENCEm043 | 2005-09-26 | 23: 29: 51.73 | – 08: 56: 46.1 | 16 | –387 | 1825 | 1 | 0.266 | 1134 ± 80 | 0.080 | Miknaitis et al. (2007) |
| ESSENCEm062 | 2005-09-25 | 01: 09: 52.902 | + 00: 36: 19.03 | 14 | –719 | 1829 | 729 | 0.314 | 1340 ± 94 | 0.067 | Miknaitis et al. (2007) |
| ESSENCEm075 | 2005-09-26 | 23: 24: 42.29 | – 08: 29: 08.7 | 16 | –708 | 2209 | 360 | 0.102 | 423 ± 30 | 0.099 | Miknaitis et al. (2007) |
| ESSENCEn263 | 2005-11-22 | 02: 05: 14.95 | – 04: 56: 39.1 | 40 | –410 | 1820 | 1421 | 0.36264 | 1549 ± 109 | 0.070 | Albareti et al. (2017) |
| ESSENCEn278 | 2005-11-24 | 23: 28: 17.55 | – 09: 23: 12.4 | 22 | –446 | 1766 | 296 | 0.304 | 1297 ± 91 | 0.109 | Miknaitis et al. (2007) |
| ESSENCEn326 | 2005-11-24 | 23: 29: 58.59 | – 08: 53: 12.5 | 16 | –446 | 1766 | 291 | 0.26316 | 1128 ± 79 | 0.082 | Adelman-McCarthy et al. (2008); Abazajian et al. (2005); Koester et al. (2007) |
| ESSENCEn400 | 2005-11-26 | 01: 13: 13.26 | – 00: 23: 25.9 | 16 | –781 | 1767 | 676 | 0.424 | 1811 ± 127 | 0.085 | Miknaitis et al. (2007) |
| ESSENCEp425 | 2005-11-24 | 23: 29: 56.19 | – 08: 34: 24.3 | 20 | –767 | 1766 | 291 | 0.458 | 1956 ± 137 | 0.085 | Miknaitis et al. (2007) |
| ESSENCEp434 | 2005-11-24 | 01: 12: 40.25 | + 00: 14: 56.6 | 15 | –779 | 2129 | 683 | 0.339 | 1447 ± 101 | 0.094 | Miknaitis et al. (2007) |
| ESSENCEq002 | 2006-09-16 | 02: 05: 12.945 | – 03: 39: 00.723 | 15 | –1029 | 1546 | 64 | 0.3469 | 1482 ± 104 | 0.064 | Narayan et al. (2016) |
| ESSENCEq222 | 2006-09-11 | 01: 12: 03.864 | – 00: 01: 28.9452 | 19 | –1070 | 1838 | 387 | 0.22637 | 965 ± 68 | 0.083 | Adelman-McCarthy et al. (2008); Albareti et al. (2017) |
| ESSENCEr185 | 2006-10-31 | 01: 11: 48.245 | – 00: 29: 49.46 | 12 | –1120 | 1428 | 337 | 0.18011 | 767 ± 54 | 0.066 | Adelman-McCarthy et al. (2008); Albareti et al. (2017) |
| ESSENCEw317 | 2006-11-14 | 01: 13: 24.658 | + 00: 51: 27.757 | 28 | –778 | 1774 | 312 | 0.3361 | 1435 ± 101 | 0.070 | Narayan et al. (2016) |
| Hawk | 2004-11-05 | 12: 35: 41.16 | + 62: 11: 37.19 | 211 | –281 | 2315 | 163 | 0.49673 | 2129 ± 149 | 0.031 | Magnelli et al. (2011); Wirth et al. (2004) |
| HST04Sas | 2004-05-23 | 12: 36: 54.125 | + 62: 08: 22.21 | 213 | –118 | 2481 | 329 | 0.44643 | 1914 ± 134 | 0.031 | Kobulnicky & Kewley (2004); Wirth et al. (2004) |

Notes. Table 1 is published in its entirety in the electronic edition of the Astrophysical Journal. A portion is shown here for guidance regarding its form and content.

\(^{a}\) Number of GALEX observations in both bands.

\(^{b}\) Number of days between the first GALEX observation in either band and the discovery date.

\(^{c}\) Number of days between the discovery date and the last GALEX observation in either band.

\(^{d}\) Number of days between the discovery date and the next GALEX observation in either band.

\(^{e}\) \( V \)-band galactic extinction

(This table is available in its entirety in machine-readable form.)
nebular spectrum (Mazzali et al. 2018; Tucker et al. 2020). We also report seven NUV nondetections for SN 2007on between $t_{\text{disc}} + 724$ days and $t_{\text{disc}} + 753$ days, where we constrain the NUV luminosity to $<1.28 \times 10^{36}$ erg s$^{-1}$ Å$^{-1}$. Challis & Hora (2008) reported that a spectrum of SN 2008hv taken before maximum was consistent with a normal SN Ia, though Marion et al. (2008) suggested it to be a high-velocity-expansion SN Ia (see Wang et al. 2008). SN 2009gf was found to be a normal SN Ia several days before maximum (Somero et al. 2009). Caldwell (2010) likewise identified SN 2010ai as a normal SN Ia a few days before peak brightness. Of the four SNe Ia, only SN 2007on has GALEX observations after $t_{\text{disc}} + 60$ days, and none of our detections are of an unusually high UV flux, which would indicate a potential instance of CSM interaction.

3.2. Nondetections & Luminosity Limits

We observe no evidence of CSM interaction in any of the 1980 SNe Ia in our sample. All of the detections are either near-peak normal SNe Ia or detections of unrelated events. We can, however, convert our nondetections into limits on the intrinsic UV luminosity of the remaining 1076 SNe Ia. We convert flux limits into intrinsic luminosity limits by using the distances listed in Table 1 and correcting for Milky Way extinction.

Figure 5 shows all post-discovery GALEX data from our survey. Inverted triangles indicate $1\sigma$ upper limit nondetections, whereas filled points mark detections. For comparison, we also include Swift data of the normal SN Ia 2011fe (Brown et al. 2014). The interior vertical axis converts observed flux $\lambda F_\lambda$ to luminosity $\lambda L_\lambda$, corrected for Milky Way extinction.

| Name       | Date (YYYY-MM-DD) | NUV (#) | FUV (#) | $t_{\text{first}}$ (days) | $t_{\text{last}}$ (days) |
|------------|-------------------|---------|---------|---------------------------|--------------------------|
| SN1937D    | 1937-09-09        | 0       | 1       | 25295                     | 25295                    |
| SN1954B    | 1954-04-27        | 3       | 3       | 19752                     | 19342                    |
| SN1957A    | 1957-02-26        | 14      | 17      | 17128                     | 19016                    |
| SN1960F    | 1960-04-17        | 0       | 4       | 17167                     | 18278                    |
| SN1960H    | 1960-06-18        | 2       | 2       | 15984                     | 16690                    |

Notes. Table 2 is published in its entirety in the electronic edition of the Astrophysical Journal. A portion is shown here for guidance regarding its form and content.

(This table is available in its entirety in machine-readable form.)

Figure 4. GALEX light curves of the four SNe Ia detected near maximum light. The blue circles represent $\geq 3\sigma$ detections in the NUV, and the inverted pink and blue triangles represent $3\sigma$ nondetection limits in the FUV and NUV, respectively. Dashed lines and shaded regions represent the host-galaxy flux and associated $1\sigma$ uncertainty, respectively. The number of pre-discovery observations for each SN Ia in the NUV (FUV) are 34 (26) for 2007on, 3 (4) for 2008hv, 1 (0) for 2009gf, and 4 (0) for 2010ai. Near-peak Swift UV light curves from Brown et al. (2014) are included for SNe 2007on, 2008hv, and 2009gf. SN 2010ai does not have any other UV photometry available in the literature, so we include optical photometry from CfA4 (Hicken et al. 2012). The interior vertical axis converts observed flux $\lambda F_\lambda$ to luminosity $\lambda L_\lambda$, corrected for Milky Way extinction.
we use photometry from the UVM2 band because it aligns most closely with the GALEX NUV filter profile (see Figure 1). We assume a monochromatic flux density for all observations. The FUV emission from SNe Ia is expected to be an order of magnitude lower than the NUV emission (Sauer et al. 2008), which is consistent with several FUV nondetections below the UVM2 light curve for SN 2011fe.

Most of these nondetections do not rule out CSM interaction, especially at higher redshifts. Many limits for SNe Ia at higher redshifts are too weak to eliminate even near-peak SN Ia flux. There are 66 SNe Ia with upper limits below $\lambda L_\lambda = 8.4 \times 10^{40}$ erg s$^{-1}$, the luminosity of CSM interaction observed in SN 2015cp (Graham et al. 2019b). We include the two detections and 70 nondetections by Graham et al. (2019b) on Figure 5 for comparison.

The periodic nature of GALEX observations present in Figure 5 is explained by the idiosyncrasies of SN surveys and the GALEX spacecraft orbit. Similar to ground-based observations, GALEX was restricted to pointing away from the Sun while observing. This created periodic gaps in the observing cadence, as a discovered SN is likely Sun-constrained six months after discovery and again 18 months after discovery, matching the data gaps seen in Figure 5.

### 4. The Occurrence Rate of Late-onset CSM Interaction

We use our nondetection limits to constrain the fraction of SNe Ia that experience late-onset CSM interaction. To do this, we assume a simple model for the GALEX FUV and NUV and HST F275W light curves of SNe Ia-CSM, which is described in Section 4.1. In Section 4.2, we describe the injection-recovery procedure to determine the number of SNe Ia in our sample which we exclude from showing signs of CSM interaction. We also run a similar procedure on the 72 HST observations by Graham et al. (2019b). In Section 4.3, we present the results of the recovery procedure on both data sets, which we use to constrain the fraction of SNe Ia-CSM at multiple epochs in Section 4.4.

#### 4.1. CSM Emission Model

To interpret our UV nondetections, we require an understanding of how the emission properties of SNe Ia-CSM evolve with time. Recent progress has been made in the radio regime (e.g., Harris et al. 2016, 2018, 2021), but there are presently no models for the UV emission or published UV spectra of SNe Ia-CSM. The UV light-curve model we adopt follows the same basic formalism as Graham et al. (2019b). The ejecta encounter...
the CSM at time $t_{\text{start}}$ days after explosion, producing an instantaneous rise in luminosity to $L_{\text{max}}$. The luminosity remains constant at $L_{\text{max}}$ for a plateau width of $W$ days, followed by a fractional decline in flux per 100 days $\Phi$. $L_{\text{max}}$ and $t_{\text{start}}$ are poorly constrained, due to the small number of known late-onset SNe Ia-CSM, but estimates for $W$ and $\Phi$ can be deduced from prior observations of SNe Ia-CSM. We adopt a plateau width of $W = 250$ days and $\Phi = 0.3$, to match the observations of PTF11kx (Silverman et al. 2013b; Graham et al. 2017). While these parameters presumably vary over some range, these simple assumptions are necessary to reduce the total number of parameters.

As GALEX observed in two filters (NUV and FUV), compared to the single HST UV filter utilized by Graham et al. (2019b), knowledge of the underlying spectral energy distribution (SED) is required to properly model the filter-specific luminosity. We use two simple models for the CSM emission: a flat-spectrum model and a line-emission model derived for Type II SNe interacting with nearby CSM.

The flat-spectrum model assumes a constant luminosity $L_\lambda$ for all filters (i.e., $L_{\text{NUV}}(t) \equiv L_{\text{FUV}}(t) \equiv L_{\text{F275W}}(t)$). If the CSM emission is continuum-dominated, this approximation is adequate if the continuum is roughly blackbody and peaks in the UV, as was the case for SN 2005gj at early times (Aldering et al. 2006). However, it is likely that SNe Ia-CSM are only continuum-dominated in the earliest stages of CSM interaction.

The line-emission model is derived from the Chevalier & Fransson (1994) model spectrum for Type II SNe interacting with nearby CSM. Although it was developed for core-collapse SNe, the physical processes governing the ejecta–CSM interaction are similar. In this model, all the UV emission is due to lines as shown in Figure 6 for one year after explosion. The one-year post-explosion model line ratios from Chevalier & Fransson (1994) agree well with the inferred emission-line ratios for SN 2015cp (Graham et al. 2019b) and PTF11kx (Dilday et al. 2012; Silverman et al. 2013b). The line width is assumed to be 2000 km s$^{-1}$, consistent with observations of SNe Ia-CSM emission lines (mainly He I) several months to years after maximum light (e.g., Kotak et al. 2004; Aldering et al. 2006; Silverman et al. 2013b, 2013a; Graham et al. 2017, 2019b).

The line-emission model provides an avenue for probing SNe Ia-CSM at higher redshifts than previous studies. To determine $L_{\text{max}}$, the spectrum is first redshifted to the SN Ia redshift and then integrated over the GALEX or HST filters.

The Ly$\alpha$ emission line, the strongest emission line in the model by a factor of $\sim 6$, enters the GALEX FUV filter at $z \approx 0.1$. Figure 7 shows the specific luminosity for each filter as a function of redshift, highlighting the importance of FUV observations for moderate-redshift SNe Ia.

We use a dimensionless scale factor $S$ to calibrate the models to known SNe Ia-CSM, where we define $S = 1$ at the observed luminosity of CSM interaction in SN 2015cp, $L_{\text{F275W}} = 3.1 \times 10^{37}$ erg s$^{-1}$ Å$^{-1}$ at $z = 0.0413$ (Graham et al. 2019b). On this scale, PTF11kx is $S = 19$ and SN 2005gj is $S = 54$, as shown in Table 3.

### 4.2. Injection Procedure

The model light curves are injected into the GALEX and HST data as early as 0 days after discovery. To eliminate contamination from near-peak UV emission, we only search for CSM emission for observations at $t > t_{\text{disc}} + 50$ days, reducing the GALEX sample to 1003 SNe Ia. The wide luminosity plateau allows models with early $t_{\text{start}}$ to be constrained by later observations. We also remove observations with $>3\sigma$ detections, whether they are near-peak detections, unrelated events, or spurious detections (see Section 3.1). For objects in the HST survey, we convert their 50% limiting magnitudes (see Table 3 in Graham et al. 2019b) to $3\sigma$ upper limits on the intrinsic UV luminosity.

We apply an “SED correction factor” to the reported fluxes from GALEX and HST before injection. Because GPHOTON reports monochromatic AB magnitudes (Million et al. 2016), it inherently assumes an SED that is flat in $F_\nu$. To make meaningful comparisons to the model CSM emission, especially the line-emission model, it is necessary to replace this assumed spectrum with the flat and line-emission models as a function of redshift. The correction factor is calculated by...
shifting the model spectrum by the redshift of the source, integrating over the given filter, and dividing by the flux of the AB magnitude zero point, $F_{\text{AB}} = 3.63 \times 10^{-25} \text{erg s}^{-1} \text{cm}^{-2} \text{Hz}^{-1}$, integrated over the same filter. We set the scale so that the correction factor for an object with $z = 0.0413$ (i.e., SN 2015cp) in the F275W band is equal to one.

We sample $t_{\text{start}}$ from a uniform distribution relative to $t_{\text{disc}}$ of 0–2500 days, and we logarithmically sample $S$ over 0.01–100. For each target, we randomly sample $N = 10,000$ instances of $t_{\text{start}}$ and $S$ from this parameter space. The generated model light curve is then injected into the target SN Ia light curve. If the injected signal reaches $\geq 3\sigma$, that SN Ia is excluded from showing CSM interaction at those parameters. Targets in the GALEX sample are excluded if the significance threshold is reached in either filter.

### 4.3. Recovery Results

Figure 8 shows 2D histograms of the number of excluded SNe Ia as a function of $t_{\text{start}}$ and $S$. We also outline the model parameter space where the two SNe Ia-CSM observed by Graham et al. (2019b), ASASSN-15og and SN 2015cp, are recovered by the injection-recovery procedure. The actual HST detections correspond to $S \approx 1.5$ and $S = 1$, respectively.

The horizontal axis of Figure 8 bins $t_{\text{start}}$ in 100-day increments. We do not display results beyond $t_{\text{disc}} + 2000$ days, as very few SNe Ia could have been detected at such late times because of the ~3600 day spacecraft lifetime combined with many SN surveys only starting after launch.

The scale factor $S$ on the vertical axis of Figure 8 is binned into 20 logarithmic increments. Along the vertical axis, we mark several known SNe Ia-CSM as a proxy for the strength of the CSM emission. As only SN 2015cp was observed in the UV (Graham et al. 2019b), we estimate $S$ using the observed H$\alpha$ emission relative to SN 2015cp,

$$S \equiv \frac{L_{\text{H}\alpha}}{L_{\text{H}\alpha}(15cp)},$$

and provide estimates for comparison SNe Ia in Table 3. We also include similar ratios for two tentative SNe Ia-CSM, ASASSN-18tb/SN 2018fhw (Kollmeier et al. 2019; Valdery et al. 2019) and ATLAS18qtd/SN 2018cqj (Prieto et al. 2020; Tucker & Shappee 2020), which showed weak H$\alpha$ emission after peak brightness. Both events were subluminous SNe Ia, so their scale factors are well below SN 2015cp.

The number of excluded SNe Ia in the GALEX sample skews heavily to scale factors of $S \geq 10$, while the HST sample has comparatively little dependence on $S$. This is partly a function of redshift because, as the distance to the SN Ia increases, the minimum detectable CSM interaction luminosity also increases. The GALEX sample, by definition, includes SNe Ia up to $z = 0.5$ with an average of $z \approx 0.238$ (see Figure 3), while the targets observed by Graham et al. (2019b) are much closer ($z \ll 0.08$) and more evenly distributed in redshift (see their Table 1). At large $S$ (i.e., SN 2005gj–like events), GALEX can exclude many more SNe Ia than HST due to the much larger sample size.

The HST survey also has fainter flux limits than GALEX. Graham et al. (2019b) report limiting AB magnitudes between 25.5 and 26 mag, while GALEX has a limiting AB magnitude of $m_{\text{F275W}} \approx 23.5$ mag for the Medium Imaging Survey or $\sim 20.5$ mag for the All-Sky Survey (Martin et al. 2005). This leads Graham et al. (2019b) to report UV luminosity limits that are one or two orders of magnitude lower than ours for targets at similar $z$, causing the GALEX sample to perform worse than the HST sample for $S \lesssim 10$.

The choice of spectral model has a large effect on the results for the GALEX sample but not for HST. As Figure 7 shows, once the $L_{\text{LyC}}$ emission line enters the FUV band at $z \approx 0.1$, FUV luminosity dominates at higher redshifts compared to the other bands. The variation of this and several other emission lines introduces an additional redshift dependence in the line-emission model that is absent in the flat-spectrum model. As a result, the number of SNe Ia excluded by the line-emission model greatly increases above $S \approx 10$ (i.e., PTF11kx-like events or even stronger), to a maximum of 302 SNe Ia at $70 \lesssim S \lesssim 100$ in the top left plot of Figure 8.

### 4.4. Observational Constraints

These results allow constraints to be placed on the occurrence rate of SNe Ia interacting with nearby CSM, $f_{\text{CSM}}$, at multiple epochs. Using a noninformative Jeffreys prior (Jeffreys 1946), we estimate the 90% binomial proportion confidence interval (C.I.; see Brown et al. 2001) for $f_{\text{CSM}}$. Within a given range of $S$ and $t_{\text{start}}$ values, we refer to the number of excluded SNe Ia as the “trials” and the number of UV detections as the “successes.”

Figure 9 presents the resulting upper bound of the 90% C.I. for $f_{\text{CSM}}$ for the GALEX and HST samples. The CSM model parameters are binned to the same intervals as in Figure 8, and the color scale is inverted to emphasize the inverse correspondence between the number of excluded SNe Ia and the upper limit on $f_{\text{CSM}}$. For the majority of our epochs, we have no detections of CSM interaction, resulting in the lower bound of the 90% C.I. being essentially zero for most parameter bins.

The HST survey places tighter constraints on $f_{\text{CSM}}$ below $S \approx 3$, though this varies with $t_{\text{start}}$. Few SNe Ia were observed by Graham et al. (2019b) after $t_{\text{disc}} + 1500$ days, limiting the effectiveness in that regime. By construction, the number of

### Table 3

| SN           | $L_{\text{H}\alpha}$ ($10^{39}$ erg s$^{-1}$) | $S$ | Epoch (days) | Source               |
|--------------|---------------------------------------------|-----|--------------|----------------------|
| SN 2005gj    | 118.                                        | 54. | +111         | Prieto et al. (2007)  |
| PTF11ks      | 40.6                                        | 19. | +371         | Silverman et al. (2013b) |
| SN 2015cp    | 2.2                                         | 1   | +694         | Graham et al. (2019b) |
| ASASSN-18tb/SN 2018fhw | 0.22                                      | 0.10 | +139         | Kollmeier et al. (2019) |
| ATLAS18qtd/SN 2018cqj | 0.038                                     | 0.02 | +193         | Prieto et al. (2020)  |
SNe Ia excluded from exhibiting CSM interaction is very similar for the line-emission and flat-spectrum models because the F275W luminosity is defined to be the same across both models for $S = 1$ at the redshift of SN 2015cp ($z = 0.0413$, Graham et al. 2019b). Furthermore, because the SNe Ia observed in the HST sample are all nearby ($z \approx 0.034$), emission lines do not move in and out of the filter. As the HST limiting magnitudes were also similar for most of its targets, there is little dependence on $S$ where $S \approx 3$, in particular at late times. There is also a stark difference between the line-emission and flat-spectrum models. As discussed in Section 4.1, the effectiveness of the FUV band...
in the line-emission model increases dramatically for SNe Ia at $z \gtrsim 0.1$, leading to very tight constraints for high $S$. By contrast, the upper 90% C.I. for the flat-spectrum model decreases more smoothly with larger $S$, as it is driven mostly by sample size. More stringent constraints on $f_{\text{CSM}}$ can be obtained by analyzing the two surveys collectively. There is no overlap between targets in both samples, so we simply combine the number of SNe Ia excluded by each study to serve as the total number of binomial trials. As no SNe Ia-CSM were detected by GALEX, the number of successes is equal to the number of HST detections.

Figure 10 presents 90% confidence intervals on the rate of CSM interaction among SNe Ia in the GALEX and HST samples alongside the combined sample ("All UV"). As before, confidence intervals are binned at 100-day increments of $t_{\text{start}}$. Each panel is a horizontal slice of Figure 9 and presents statistics for a single range of scale factors. We provide the results for scale factors of $S \approx 1$, $S \approx 10$, and $S \approx 100$, as these values roughly correspond to the strength of CSM interaction observed in SN 2015cp, PTF11kx, and SN 2005gj, respectively.

Included alongside our constraints on $f_{\text{CSM}}$ are external constraints we derive from the All-Sky Automated Survey for...
SuperNovae (ASAS-SN; Shappee et al. 2014; Kochanek et al. 2017) and Zwicky Transient Facility (ZTF; Bellm et al. 2019; Graham et al. 2019a) surveys. Over the first four years of operations, ASAS-SN observed three SNe Ia-CSM out of 464 total SNe Ia (Holoien et al. 2017b, 2017a, 2017c, 2019), leading to a 90% C.I. on the occurrence rate of 0.23% $\lesssim f_{\text{CSM}} \lesssim 1.51%$. The ZTF 2018 sample (Yao et al. 2019) had only one SN Ia-CSM out of 127 SNe Ia, leading to 0.14% $\lesssim f_{\text{CSM}} \lesssim 3.04%$. These crude estimates do not account for completeness in each survey, but considering SNe Ia-CSM are typically overluminous compared to their normal counterparts, they are likely to be overrepresented in these catalogs.

Finally, we constrain $f_{\text{CSM}}$ for broader ranges of $t_{\text{start}}$. Table 4 presents upper 90% confidence limits on the rate of late-onset CSM for several ranges of $t_{\text{start}}$ and $S$. We use only the line-emission spectral model, because we consider it to be more representative of the true SED. For each given $t_{\text{start}}$ range, we report the corresponding radius of the innermost shell of CSM $r_{\text{CSM}}$, assuming an ejecta velocity $v_{\text{ej}} \approx 20,000 \text{km s}^{-1}$ (Garavini et al. 2005). We also report the eruption time $t_{\text{erupt}}$, in years before the SN Ia explosion, for material at $r_{\text{CSM}}$ assuming a shell expansion velocity $v_{\text{exp}} \approx 100 \text{km s}^{-1}$, similar to PTF11kx (Dilday et al. 2012).

Strong interactions similar to that observed in SN 2005gj are rare: we constrain $f_{\text{CSM}} \lesssim 1.6\%$ for $S \approx 100$ between 0 – 500 years.
days after discovery and $f_{\text{CSM}} \lesssim 1\%$ between 500 and 1000 days. We can also place tight constraints on the occurrence rate of PTF11kk-like events ($S \approx 10$), for which we find $f_{\text{CSM}} \lesssim 5.1\%$ between $0 \leq t_{\text{start}} \leq 500$ days and $f_{\text{CSM}} \lesssim 2.7\%$ between $500 \leq t_{\text{start}} \leq 1000$ days. GALEX is much less effective at constraining $f_{\text{CSM}}$ for SN 2015cp-like events ($S \approx 1$), but still manages a small improvement over the statistics from HST alone, with $f_{\text{CSM}} \lesssim 14\%$ between $0 \leq t_{\text{start}} \leq 500$ days and $f_{\text{CSM}} \lesssim 4.8\%$ between $500 \leq t_{\text{start}} \leq 1000$ days. This is consistent with the previous estimate of $f_{\text{CSM}} \lesssim 6\%$ for CSM within $r_{\text{CSM}} \approx 3 \times 10^{17}$ cm reached by Graham et al. (2019b). Finally, for events on the scale of ASASSN-18tb ($S \approx 0.1$), we constrain $f_{\text{CSM}} \lesssim 16\%$ between $0 \leq t_{\text{start}} \leq 500$ days and $f_{\text{CSM}} \lesssim 8.6\%$ between $500 \leq t_{\text{start}} \leq 1000$ days almost exclusively from the HST data. These results represent the most thorough attempt thus far to constrain $f_{\text{CSM}}$ for an unbiased sample of SNe Ia.

5. Conclusions

We present results from our search for late-onset CSM interaction among SNe Ia. GALEX serendipitously observed 1080 SNe Ia at $z < 0.5$ both before and after discovery. Four SNe Ia (SNe 2007on, 2008hv, 2009gf, and 2010ai) are detected near-peak in the GALEX NUV filter, but no evidence of SNe Ia interacting with a nearby CSM was found.

With the UV nondetections of 1003 SNe Ia, we implement an injection-recovery procedure to estimate the intrinsic fraction of SNe Ia interacting with CSM, $f_{\text{CSM}}$. Due to the lack of models in the literature addressing the UV emission and light-curve evolution of SNe Ia-CSM, we make several simple assumptions about the underlying SED and its temporal evolution. Combining our GALEX observations with the HST survey performed by Graham et al. (2019b), we can constrain $f_{\text{CSM}}$ for a broad range of scale factors $S$ relative to SN 2015cp (a proxy for the CSM luminosity) and times when the SN ejecta first encounters the CSM $t_{\text{start}}$.

We strongly constrain the most luminous events, such as those similar to SN 2005gj ($S \approx 100$, or $L_{\text{UV}} \sim 10^{41}$ erg s$^{-1}$), at high confidence with $f_{\text{CSM}} \lesssim 1.6\%$ between 0 – 500 days after discovery and $f_{\text{CSM}} \lesssim 1\%$ between 500 and 1000 days. Moderate-luminosity CSM interactions similar to that seen in PTF11kk ($S \approx 10$, or $L_{\text{UV}} \sim 10^{40}$ erg s$^{-1}$) are still rare, with $f_{\text{CSM}} \lesssim 5.1\%$ and $f_{\text{CSM}} \lesssim 2.7\%$, respectively, for the same timescales. SN 2015cp-like events ($S \approx 1$, or $L_{\text{UV}} \sim 10^{39}$ erg s$^{-1}$) are constrained to $f_{\text{CSM}} \lesssim 4.8\%$ between 500 and 1000 days, with weaker constraints at other timescales. For the weakest CSM interactions (e.g., ASASSN-18tb), our observations do not place meaningful constraints, highlighting the need for further monitoring of SNe Ia out to late epochs, especially in the UV where CSM is easy to distinguish from the underlying ejecta emission.

Finally, this study reinforces the need for consistent monitoring of SNe Ia at late times. Since observations of most SNe Ia last for just a few months after the explosion, any instance of late-onset CSM interaction is likely to be systematically missed. In addition, the ability to constrain $f_{\text{CSM}}$ is limited by the lack of models for SNe Ia-CSM in the UV. As SNe Ia-CSM potentially originate through the SD progenitor channel, our constraints may inform future studies on the nature of SN Ia progenitors.

We thank Christopher Kochanek and Connor Auge for providing useful comments on the manuscript. We thank Chase Million and Scott Fleming for useful discussions about GPHOTON. We also thank Greg Aldering, Melissa Graham, and David Sand for their help searching for archival classification spectra.

L.O.D. acknowledges support from Research Experience for Undergraduates program at the Institute for Astronomy, University of Hawaii-Manoa funded through NSF grant No. 6104374. L.O.D. would like to thank the Institute for Astronomy for their kind hospitality during the course of this project. M.A.T. acknowledges support from the DOE CSGF.
through grant No. DE-SC0019323. B.J.S. is supported by NSF grant Nos. AST-1907570, AST-1920392, and AST-1911074.

This research has made use of the SVO Filter Profile Service\textsuperscript{12} supported from the Spanish MINECO through grant AYA2017-84089. This research also makes use of the NASA/IPAC Extragalactic Database (NED), which is funded by the National Aeronautics and Space Administration and operated and maintained by the California Institute of Technology.

\textit{Software:} GPHOTON (Million et al. 2016), AstroPy\textsuperscript{13} (Astropy Collaboration et al. 2013, 2018), astroquery (Ginsburg et al. 2019), statsmodels (Seabold & Perktold 2010), SciPy (Virtanen et al. 2020), NumPy (Harris et al. 2020), Matplotlib (Hunter 2007), and pandas (McKinnney 2010; Reback et al. 2021).

### Appendix A

**New Redshift Measurements**

For SNe Ia with redshifts given to <2 decimal places, we attempt to manually improve the redshift determination based on available data. The new redshifts are provided in Table 5 including the catalog redshift, the redshift derived in this work, the spectrum data source, and the method used to measure the redshift and associated uncertainty. SNe 2009cp and 2009cu have publicly available reduced spectra in the Weizmann Interactive Supernova Data Repository (WISEREP; Yaron & Gal-Yam 2012) whereas SNe 2009kt, 2009kv, and 2009kx have Gemini Multi-Object Spectrograph (GMOS; Hook et al. 2004) data available through the Gemini Observatory Archive. The raw GMOS spectra were reduced using the GMOS Data Reduction Cookbook\textsuperscript{14} with calibration frames taken near the time of observation.

The spectrum of SN 2009kt shows host-galaxy emission lines evident in the extracted spectrum, and the host-galaxy origin is confirmed via extended emission in the 2D spectra. Emission lines from H\textalpha, H\beta, the [OIII] 4959/5007 Å doublet, and the [SII] 6716/6731 Å doublet are observed, and we fit these lines simultaneously to derive the host-galaxy redshift.

The remaining SNe Ia do not have host-galaxy lines in their spectra, so we estimate a redshift using the SuperNova IDentification code (SNID; Blondin & Tonry 2007). After confirming the best matches to the observed spectrum are SNe Ia, we restrict the correlation templates to only SNe Ia and use the 10 best matches to estimate the redshift and its uncertainty.

### Appendix B

**Photometric Precision and Stability**

GALEX photometry has been used previously in co-added images (e.g., Leroy et al. 2019; Bracco et al. 2020) and to study short-term intra-visit stellar variability (e.g., Boudreaux et al. 2017; Tucker et al. 2018; Rowan et al. 2019). However, to our knowledge, it has never been used for long-term monitoring as we do here. Thus, we want to include as much photometry as possible without sacrificing photometric quality and stability. To these ends, we run several photometric tests to validate our assumptions on the GALEX photometry.

The DETRAD column output by GPHOTON denotes the average photon event distance from detector center. The “detector edge” flag is generated when any photon event occurs at >0.5° from detector center, yet the GALEX detectors have radii of ≈0.62. Photometry near the edge of the detectors is untrustworthy, as the detector response at the edge is poorly characterized (Morrissey et al. 2007) and has reduced count rates due to the GALEX dithering process. However, the 0.5° cut is likely too conservative for our purposes, so we explore using a larger maximum radius to improve our photometric completeness.

Figure 11 provides the difference between the MCAT reference magnitudes and the GAPERTURE-derived magnitudes for an aperture radius of 6° (the GALEX MCAT APER4 radius). We see there is little difference between MCAT and GAPERTURE until ∼0.6° from detector center. To ensure photometric quality, we use an updated DETRAD cut at 0.6°, increasing our effective GALEX detector size by ∼45%.

### Appendix C

**Host-galaxy Systematic Uncertainty**

A key component of our analysis is requiring GALEX observations both before and after the SN Ia discovery date so the host-galaxy flux can be effectively removed. SNe Ia with >5 host-galaxy observations have sufficient data to both estimate the mean host-galaxy flux and the ensuing uncertainty (see Section 2.5). However, for SNe Ia host galaxies with <5 observations, we risk underestimating the true uncertainty of the host-galaxy flux and thus underestimating the ensuing host-subtracted SN fluxes. Therefore, we calculate a systematic uncertainty for host galaxies with few observations, to ensure our results are statistically robust.

Figure 12 compares the reference MCAT magnitude to the single-epoch GPHOTON aperture photometry magnitude for a given MCAT source. This provides a rough estimate of the systematic uncertainty as a function of UV brightness. We note that the NUV suffers from higher scatter, due to increased source crowding, even though the FUV typically has fewer detected photons (Million et al. 2016). We implement adaptive binning when computing the bin size, requiring 100 stars per bin. This approach prevents brighter bins from having very few objects per bin and retains roughly equal bin sizes for higher magnitudes. For each bin, we apply iterative sigma clipping then compute the weighted mean and standard deviation shown as the solid colored lines in Figure 12. We include an anchor at
the bright end of the distribution from Morrissey et al. (2007) of Δm = ± 0.03 (0.05) mag for the NUV (FUV) data, respectively. We approximate the systematic uncertainty with a power-law function, Δm_{sys} = A \left( \frac{m}{1 \text{mag}} - 14 \right)^B, where A and B are fitted coefficients and $m$ is the filter-specific GALEX

Figure 11. Difference between MCAT magnitudes and GAPERTURE magnitudes as a function of average detector radius. Individual point sizes are inversely proportional to their respective uncertainties. Bold points mark the median and 90% confidence interval for equally spaced 0.02 wide bins. The dotted gray line signifies the nominal GPHOTON detector edge flag set at >0.5 from center, and the solid gray line signifies our updated cut at >0.6.

Figure 12. Difference between MCAT and GAPERTURE magnitudes as a function of MCAT magnitude. Colored points are individual sources with the point size proportional to 1/σ (i.e., smaller point = larger uncertainty). Solid colored lines are the binned weighted mean for each filter using adaptive bin sizes of 100 sources (see text). Dashed lines represent simple power-law fits to the binned data.
magnitude. To reduce the covariance in the fitting process, \( m \) is offset by 14 mag. We find \( A_{\text{NUV}} = (4.94 \pm 0.83) \times 10^{-7} \text{mag} \), \( B_{\text{NUV}} = 6.17 \pm 0.08 \) and \( A_{\text{FUV}} = (4.78 \pm 1.61) \times 10^{-4} \text{mag} \), \( B_{\text{FUV}} = 2.60 \pm 0.16 \). These are rough approximations but should suffice for our purposes of preventing an underestimate of the host-galaxy flux.

### Appendix D

#### False Positives

ESSENCEn263 has significant NUV detections between 1421 and 1820 days after discovery, with a maximum 11.9\( \sigma \) detection relative to the host flux as shown in Figure 13. However, the host-galaxy is a known broad-line AGN (SDSS ObjID = 1237679253596340445; Albareti et al. 2017) and offset from the position of ESSENCEn263 by \( \sim 2''/6 \) but within our 6''-radius aperture. Figure 14 presents GMAP images for ESSENCEn263, which confirm the NUV excess is centered on the host-galaxy and not the SN Ia location.

**References**

Abazajian, K., Adelman-McCarthy, J. K., Agüeros, M. A., et al. 2005, ApJ, 129, 1755
Adelman-McCarthy, J. K., Agüeros, M. A., Allam, S. S., et al. 2008, ApJS, 175, 297
Albareti, F. D., Allende Prieto, C., Almeida, A., et al. 2017, ApJS, 233, 25
Aldering, G., Antilogus, P., Bailey, S., et al. 2006, ApJ, 650, 510
Astropy Collaboration, Robitaille, T. P., Tollerud, E. J., et al. 2013, A&A, 558, A33
Astropy Collaboration, Price-Whelan, A. M., Sipőcz, B. M., et al. 2018, AJ, 156, 123

**ORCID iDs**

Liam O. Dubay @ https://orcid.org/0000-0003-3781-0747
Michael A. Tucker @ https://orcid.org/0000-0002-2471-8442
Aaron Do @ https://orcid.org/0000-0003-3429-7845
Benjamin J. Shappee @ https://orcid.org/0000-0003-4631-1149
Gagandeep S. Anand @ https://orcid.org/0000-0002-5259-2314
Soker, N., Kashi, A., García-Berro, E., Torres, S., & Camacho, J. 2013, MNRAS, 431, 1541
Somero, A., Smirnova, O., Micheva, G., et al. 2009, CBET, 1846, 1
Soumagnac, M. T., Olek, E. O., Gal-yam, A., et al. 2019, ApJ, 872, 141
Srivastav, S., Gillanders, J., Fulton, M., et al. 2021, TNSAN, 11, 1
Sternberg, A., Gal-Yam, A., Simon, J. D., et al. 2011, Sci, 333, 856
Sullivan, M., Guy, J., Conley, A., et al. 2011, ApJ, 737, 102
Thompson, T. A. 2011, ApJ, 741, 82
Trundle, C., Kotak, R., Vink, J. S., & Meikle, W. P. S. 2008, A&A, 483, L47
Tucker, M. A., Fleming, S. W., Pelisoli, I., et al. 2018, MNRAS, 475, 4768
Tucker, M. A., & Shappee, B. J. 2020, RNAAS, 4, 80
Tucker, M. A., Shappee, B. J., Vallely, P. J., et al. 2020, MNRAS, 493, 1044
Tully, R. B., Courtois, H. M., & Sorce, J. G. 2016, AJ, 152, 50
Vallely, P. J., Fausnaugh, M., Jha, S. W., et al. 2019, MNRAS, 487, 2372
Virtanen, P., Gommers, R., Oliphant, T. E., et al. 2020, Nature Methods, 17, 261
Walder, R., Folini, D., & Shore, S. N. 2008, A&A, 484, L9
Wang, L., Baade, D., Höflich, P., et al. 2004, ApJL, 604, L53
Wang, X., Li, W., Filippenko, A. V., et al. 2008, ApJ, 675, 626
Webbink, R. F. 1984, ApJ, 277, 355
Wheeler, J. C., Locar, M., & McKee, C. F. 1975, ApJ, 200, 145
Whelan, J., & Iben, I. J. 1973, ApJ, 186, 1007
Wiersma, R. P. C., Schaye, J., & Theuns, T. 2011, MNRAS, 415, 353
Wirth, G. D., Willmer, C. N. A., Amico, P., et al. 2004, AJ, 127, 3121
Wood-Vasey, W. M., Miknaitis, G., Stubbs, C. W., et al. 2007, ApJ, 666, 694
Wood-Vasey, W. M., Wang, L., & Aldering, G. 2004, ApJ, 616, 339
Yao, Y., Miller, A. A., Kulkarni, S. R., et al. 2019, ApJ, 886, 152
Yaron, O., & Gal-Yam, A. 2012, PASP, 124, 668
Yoon, S. C., & Langer, N. 2003, A&A, 412, L53
York, D. G., Adelman, J., Anderson, J. E. J., et al. 2000, AJ, 120, 1579
Yuan, H. B., Liu, X. W., & Xiang, M. S. 2013, MNRAS, 430, 2188
Yungelson, L. R., Livio, M., Tutukov, A. V., & Saffer, R. A. 1994, ApJ, 420, 336
Zaroubi, S. 2002, arXiv:astro-ph/0206052