A Search for Optical AGN Variability in 35,000 Low-mass Galaxies with the Palomar Transient Factory

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Abstract

We present an analysis of the long-term optical variability for ~50,000 nearby (z < 0.055) galaxies from the NASA–Sloan Atlas, 35,000 of which are low-mass (M* < 1010 M☉). We use difference imaging of Palomar Transient Factory (PTF) R-band observations to construct light curves with typical baselines of several years. We then search for subtle variations in the nuclear light output. We determine whether detected variability is AGN-like by assessing the fit quality to a damped random walk model. We identify 417 variability-selected AGNs, including 237 with stellar masses between 107 and 1010 M☉. 75% of low-mass galaxies with AGN-like variability have narrow emission lines dominated by star formation. After controlling for nucleus magnitude, the fraction of variable AGNs is constant down to M* = 108 M☉, suggesting no drastic decline in the BH occupation fraction down to this stellar mass regime. Combining our NASA–Sloan Atlas sample with samples of nearby galaxies with broad Hα emission, we find no dependence of variability properties with black hole mass. Our PTF work demonstrates the promise of long-term optical variability searches in low-mass galaxies for finding AGNs missed by other selection techniques.

Unified Astronomy Thesaurus concepts: Active galactic nuclei (16); Dwarf galaxies (416); Variable radiation sources (1759); Sky surveys (1464); AGN host galaxies (2017)

Supporting material: machine-readable table

1. Introduction

The last decade has seen a drastic increase in the number of publicly available repeat imaging surveys. This has enabled the detection and characterization of a wide range of transient and variable phenomena, including supernovae, tidal disruption events, and active galactic nuclei (AGNs). AGNs are observed to vary across the electromagnetic spectrum on timescales ranging from hours to years. Variability itself has long been a powerful tool for identifying AGNs (Ulrich et al. 1997; Geha et al. 2003; Sesar et al. 2007; Schmidt et al. 2010; MacLeod et al. 2011; Choi et al. 2014; Heinis et al. 2016).

The identification of AGNs via long-term optical variability is particularly interesting in the context of AGNs in low-mass galaxies (M* < 1010 M☉). Massive black holes (BHs; M BH ≥ 107 M☉) in low-mass galaxies are elusive; their relatively small sphere of influence makes them infeasible to find dynamically beyond ~5 Mpc (see den Brok et al. 2015; Nguyen et al. 2017, 2018, 2019 for examples of dynamical detections in low-mass galaxies within 5 Mpc). Thus, in general, searches for BHs in low-mass galaxies focus on signs of BH accretion rather than on dynamical signatures.

The first efforts to identify AGNs in low-mass galaxies in significant numbers used optical spectroscopic selection techniques. Using Sloan Digital Sky Survey (SDSS) data, Greene & Ho (2004, 2007) searched for broad Hα emission indicative of low-mass black holes with M BH ≤ 106 M☉. Reines et al. (2013) analyzed SDSS spectroscopy for 25,000 emission-line galaxies with stellar masses less than the Large Magellanic Cloud (i.e., M* < 3 × 109 M☉), and found 136 with optical emission-line ratios indicative of AGN activity (based on the BPT diagram; Baldwin et al. 1981; Kauffmann et al. 2003; Kewley et al. 2006).

While optical emission-line ratios are a secure method of identifying AGNs in low-mass galaxies (Baldassare et al. 2016), there is likely a population that is undetected due to selection effects that are increasingly relevant at low stellar masses. In particular, star formation dilution and low-metallicity effects are thought to compromise the detection of AGNs in low-mass galaxies. Star formation can dilute the contribution of a weak and/or low-mass AGN to the optical emission lines. This is especially true when considering the 3σ spectroscopic fiber of the SDSS, which sometimes encloses the entire spatial extent of a dwarf galaxy (Trump et al. 2015; Dickey et al. 2019). Additionally, low galaxy metallicity has the effect of lowering the [N II]-to-Hα ratio and pushing objects to the left and out of the AGN regime on the classic BPT diagram (Groves et al. 2006; Cann et al. 2019).

In Baldassare et al. (2018), we used SDSS Stripe 82 data to search for low-level optical photometric variability characteristic of AGNs in a sample of ~28,000 galaxies with stellar masses from 107 to 1012 M☉ from the NASA–Sloan Atlas. We found 135 galaxies with AGN-like optical photometric variability, as determined by the goodness-of-fit to a damped random walk model (Kelly et al. 2009; Kozłowski et al. 2010; Butler & Bloom 2011). The variable AGN host galaxies ranged in stellar mass from ~108 to 1011 M☉. Interestingly, there was a difference in the optical spectroscopic properties of the high-mass (M* > 1010 M☉) and low-mass (M* < 1010 M☉) subsamples. Among the high-mass galaxies, almost 100% had narrow-line ratios placing them in the AGN or composite regions of the BPT diagram. On the other hand, 50% of the low-mass galaxies had narrow emission-line ratios placing them in the star-forming region of the BPT diagram, indicating that optical variability can identify AGNs missed by other selection techniques. In the era of the Vera C. Rubin...

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Observatory Legacy Survey of Space and Time (LSST; Ivezić et al. 2008), which will image the entire visible sky every three nights, this represents an incredibly promising technique for finding substantial numbers of obscured or otherwise undetected AGNs in low-mass galaxies.

In this paper, we expand our search for variable AGN to the Palomar Transient Factory, which has covered almost the entire northern sky (∼30,000 deg², compared to 275 deg² for SDSS Stripe 82). In Section 2, we describe our data set and samples of galaxies. In Section 3, we discuss the difference imaging and light-curve construction techniques, and the selection of variable AGNs. In Section 4, we present our variability results and search for possible relations between BH mass and variability properties. Finally, in Section 5, we compare our sample of low-mass galaxies with AGN-like variability from PTF to those selected via other techniques and discuss implications for the low-mass end of the occupation fraction.

2. Data

2.1. Palomar Transient Factory

The Palomar Transient Factory (PTF; Rau et al. 2009; Law et al. 2009) is a wide-field optical survey to study the transient and variable sky. PTF began operations in 2009, using the 48 inch Samuel Oschin Telescope at Palomar Observatory. PTF observed primarily in the R band with an exposure time of 60 s and typical 5 − σ limiting magnitude of $m_R = 20.5$ mag. The pixel size of the CCD is 1″/pix. Observations were also made in the g band, but with significantly fewer epochs (the limiting g-band magnitude is $m_g = 21$). The Intermediate Palomar Transient Survey (iPTF), which built upon the PTF, improved upon data reduction and source classification using an upgraded camera. The PTF/iPTF have observed almost the entire northern sky, with some parts of the sky being imaged several thousand times. Since the PTF/iPTF has pursued various experiments and observer-proposed projects, the cadence and baseline for any given region can differ widely from the rest of the survey. These data are publicly available, and the science addressed by the PTF/iPTF span a wide range of astrophysical phenomena including supernovae (Bloom et al. 2012; Brown et al. 2012; Perley et al. 2016), cataclysmic variables, tidal disruption events (Arcavi et al. 2014; van Velzen et al. 2019), and AGNs (Rau et al. 2009; Heinis et al. 2016; Caplar et al. 2017; Gezari et al. 2017).

2.2. Galaxy Samples

We are interested in finding BHs in low-mass galaxies. In order to have accurate galaxy stellar mass estimates, we require the sample to have spectroscopic redshifts. We use the NASA–Sloan Atlas (NSA) as our parent galaxy sample. The NSA is a reprocessing of five-band SDSS DR8 photometry, combined with UV photometry from Galaxy Evolution Explorer (Blanton & Roweis 2007; Aihara et al. 2011; Blanton et al. 2011; Yan 2011). Most of the galaxies in the NSA have SDSS spectroscopy, though a small number have spectroscopic redshifts from e.g., the NASA Extragalactic Database. The NSA catalog provides a wealth of derived quantities, including spectroscopic redshifts, galaxy mass, radius, ellipticity, magnitude, and line flux measurements. We use NSA version 0, which extends out to $z = 0.055$ (hereafter, referred to as NSA0). Note that the ID numbers assigned to galaxies in the NSA0 differ from those assigned in the NSA version 1, which extends to $z = 0.15$. There are more than 145,000 galaxies in the NSA0, with a median stellar mass of $4 \times 10^7 M_\odot$.

Our Stripe 82 results (Baldassare et al. 2018) showed that above $M_\star \approx 10^{10} M_\odot$, almost all of the variable galaxies were also classified as AGNs based on their optical emission-line ratios. Thus, given limited resources, we focused our PTF analysis on low-mass galaxies. Our primary NSA0 sample is constructed to include all galaxies with stellar masses $M_\star \lesssim 2 \times 10^9 M_\odot$. Additionally, we construct light curves for any NSA galaxy near enough to the target galaxy that they are contained within the field surrounding the target galaxy. There are 78,872 galaxies below the $2 \times 10^9 M_\odot$ mass cut in the NSA with some amount of coverage in the PTF. After placing constraints on the minimum required number of data points (Section 3.1), our stellar mass-selected NSA0 analysis sample consists of 44,720 galaxies with $M_\star < 2 \times 10^9 M_\odot$. There are also 2405 galaxies more massive than this cut that were in the fields of the target galaxies and that we include in our main NSA sample. To summarize, our main NSA sample contains 47,125 galaxies spanning from $\sim 10^7$ to $10^{12} M_\odot$. This sample has a median stellar mass of $4.5 \times 10^9 M_\odot$ and a median redshift of $z = 0.035$.

In order to search for trends with BH mass, we also analyze data from ancillary samples of broad-line AGNs. Specifically, we include the Greene & Ho (2007) catalog of low-mass ($M_{BH} \lesssim 10^6 M_\odot$) broad-line AGNs, and the Reines & Volonteri (2015) compilation of broad-line AGNs in the NSA0. Greene & Ho (2007) searched the SDSS DR7 for galaxies with broad Hα emission indicative of BHs with $M_{BH} \lesssim 10^6 M_\odot$ and identified 229 galaxies meeting this criterion. These objects are generally at higher redshift than the NSA0 and so are not in our main sample. Reines & Volonteri (2015) searched for broad Hα emission in 66,945 galaxies from the NSA0. Their final sample was composed of 237 broad-line AGNs with BH masses ranging from $M_{BH} \approx 10^5 – 10^8.5 M_\odot$. While Reines & Volonteri (2015) also used the NSA0 as their parent sample, not all of their high-mass galaxies end up in our main sample.

Table 1 summarizes our main and ancillary samples, and lists the number of objects used for analysis in each sample.

| Sample                      | $N_{\text{galaxies}}$ | Redshift | $\log(M_\star/M_\odot)$ |
|-----------------------------|-----------------------|----------|--------------------------|
| Mass-selected NSA galaxies  | 44,720                | <0.055   | <10.3                    |
| Serendipitous NSA galaxies  | 2405                  | <0.055   | >10.3                    |
| Final ("main") NSA sample  | 47,125                | <0.055   | <11.8                    |
| Greene & Ho (2007)          | 82                    | <0.35    | 9.2–11.9                 |
| Reines & Volonteri (2015)   | 110                   | <0.055   | 8.9–11.5                 |

Note. Summary of samples analyzed for variability. Our main sample is drawn from the NSA catalog; this is comprised of all galaxies in the NSA0 below $2 \times 10^{10} M_\odot$ (“mass-selected NSA”) and any NSA galaxies in the field analyzed surrounding each of those (“serendipitous NSA”). The other samples are ancillary samples of broad-line AGNs that were not originally included in the main NSA sample due to the stellar mass and redshift selection.
3. Data Analysis

3.1. Difference Imaging and Light-curve Construction

Our goal is to detect low-level variability (less than a tenth of a magnitude) of point sources superposed on top of extended host galaxies. We use difference imaging to subtract off the host galaxy light before measuring any light from the galaxy nucleus. Our analysis is similar to Baldassare et al. (2018) and summarized here.

For each target galaxy we download 300′ × 300′ PTF R-band images (roughly 300 × 300 pixels), centered on the target. We use only PTF images that have seeing better than 3″. We use the R band as opposed to the g-band, since the sky coverage, baselines, and number of observations are substantially better in the R band. After retrieving all R-band images for a given target from the PTF database, we proceed with difference imaging.

We use the software Difference Imaging and Analysis Pipeline 2 (DIAPL2), which is a modified version of the Difference Imaging Analysis software (Wozniak 2000). Both are based on the difference imaging analysis introduced by Alard & Lupton (1998) and Alard (2000). The first step is to construct a template image by combining the best frames (i.e., those with the best seeing and lowest background). Then, for each individual exposure, the template image is convolved with a best-fit kernel to match the seeing of that exposure. The kernel is a sum of 2D Gaussians of different widths. The template background is also matched to that of the exposure. Finally, the convolved template is subtracted from the exposure to create a difference image.

To construct light curves for each galaxy, we carry out aperture photometry on the template and difference images. Thus, the flux value for each data point is the template value plus the difference image value. We use an aperture of 3″ centered on the galaxy nucleus as given in the NSA80. This aperture was chosen to match the seeing of the lowest-quality frames we use.

In Figure 1, we show the median $\sigma_{\text{var}}$ (or the significance that a galaxy is variable) versus the number of data points in a light curve. Based on this figure, we see that for targets with less than ~20 data points, the median measured $\sigma_{\text{var}}$ is >1 − $\sigma$ (i.e., they are more likely to be flagged as variable). This is because, with few data points, there are fewer high-quality images from which to construct a template, and an overall poorer image subtraction result. We choose to exclude light curves with less than 20 points from all further analysis. This reduces our sample from 78,872 objects to 47,125.

Light-curve baselines for the final sample range from 3 days to 2156 days, with a median baseline of 1474 days. The median number of data points is 65, and the maximum number of points in a light curve is 1625. Representative light curves for variable and non-variable galaxies are shown in Figure 2.

3.2. Detection of AGN-like Variability

We select galaxies with AGN-like variability based on the goodness-of-fit of the galaxy’s light curve to a damped random walk (DRW) model. The DRW is generally a good empirical descriptor of AGN variability (Kelly et al. 2009; MacLeod et al. 2010; Kozłowski et al. 2010; Butler & Bloom 2011), at least for observations with cadences of days to weeks (see
Kasliwal et al. 2015). In order to select targets that are both (i)
variable and (ii) have AGN-like variability, we use the software
QSO_fit (Butler & Bloom 2011). This software takes the
measured magnitude values and dates as input and returns a
best-fit DRW model, along with the quantities $\sigma_{\text{var}}, \sigma_{\text{QSO}},$ and
$\sigma_{\text{noQSO}}$. $\sigma_{\text{var}}$ is the significance that the object is variable; $\sigma_{\text{QSO}}$
is the significance that the $\chi^2$ for the damped random walk
model is better than the expected $\chi^2$ for non-AGN-like
variability; $\sigma_{\text{noQSO}}$ is the significance that the source variability
is better described by random variability.

We select objects as candidate variable AGNs if they have
$\sigma_{\text{var}} > 2$, $\sigma_{\text{QSO}} > 2$, and $\sigma_{\text{QSO}} > \sigma_{\text{noQSO}}$. All light curves and
difference images are then inspected by eye to remove spurious
variability detections due to, e.g., poor difference imaging or
bad image frames. In all, we find 417 galaxies with AGN-like variability out of 47,125 total analyzed objects.

3.3. Optical Spectroscopic Analysis

We re-analyze SDSS optical spectroscopy for all galaxies
found to have AGN-like variability to search for narrow and
broad emission-line signatures of AGN activity. Following the
same approach as Baldassare et al. (2018; see also Reines et al.
2013; Baldassare et al. 2015, 2016), we model the H$\beta$, [O III]$\lambda\lambda5007, H\sigma,$ and [N II]$\lambda\lambda6548, 6583$ emission lines. First, we
create a narrow emission-line model using the [S II]$\lambda\lambda6713$
and 6731 lines. These are forbidden transitions and thus not
produced in the denser broad-line region. We then use the
width of the [S II] lines to fit the narrow H$\sigma$ emission and the
[N II]$\lambda\lambda6548, 6684$ lines simultaneously. The width of narrow
H$\sigma$ is allowed to increase by 25% relative to the [S II] width,
and the relative amplitudes of [N II]$\lambda\lambda6548, 6684$ are fixed to
laboratory values. We next add a broader Gaussian component
representing broad H$\sigma$ emission to the model. The component
is kept as part of the model if the $\chi^2$ value of the fit improves
by 20%. If the spectrum is better fit with a broad H$\sigma$
component, we also test a model with two Gaussian
components to represent broad H$\sigma$, again keeping the
additional Gaussian if the $\chi^2$ value of the fit improves by at
least 20%. We also fit H$\beta$ and [O III]$\lambda5007$. H$\beta$ can also be fit
with an additional broad component. In all of the line fits,
the continuum is represented by a line fit across the relevant
spectral region.

If broad H$\sigma$ is present, we estimate the BH mass using the
full width half maximum (FWHM) and luminosity of the broad
H$\sigma$ component (Greene & Ho 2005). Assuming the gas in the
broad-line region is virialized, we can estimate the BH mass
with the distance to the broad-line region, and the velocity of
the broad-line region gas. The FWHM of broad H$\sigma$ gives an
estimate of the velocity of the gas in the broad-line region, and
the luminosity of broad H$\sigma$ has been found to be correlated
with the distance from the BH to the broad-line region (Greene
& Ho 2005; Bentz et al. 2009, 2013). BH masses estimated via
this technique have typical uncertainties of $\sim0.3$ dex.

4. Variability Results

In this section, we present the main results of our difference
imaging and light curve analysis. We compute the fractions of
variable AGNs found in the main NSAv0 sample and explore
how the variable fraction changes as a function of stellar mass
and baseline (Section 4.1). We also present variability results
from ancillary samples of broad-line AGNs from Greene & Ho
(2007) and Reines & Volonteri (2015) (Section 4.2). See Table 1
for a summary of the properties of each sample.

A summary of our variability fractions given in Table 2.
Care should be taken in comparing the fractions from different
groups, as they may have different magnitude distributions.

4.1. Main NSA Sample

As described in Section 2.2, there are 47,125 galaxies in our
main NSAv0 sample with 20 or more data points. The sample
ranges in stellar mass from $10^4$ to $10^{12} M_{\odot}$. By construction,
we are complete for stellar masses below $M_*=2 \times 10^{10} M_{\odot}$.
Based on the selection criteria described in Section 3.2, 417 out
of 47,125 galaxies have AGN-like variability, for an overall
variable AGN fraction of 0.9%. In Figure 3, we show the light-
curve standard deviation versus the PTF R-band magnitude for
the full sample. In general, the scatter about the median
magnitude for a given light curve increases as the magnitude
increases, i.e., there is increased scatter in light curves of fainter
objects. The sample of low-mass galaxies from the NSAv0
without AGN-like variability is presented in Table 3. Three
examples of low-mass galaxies with AGN-like variability are
shown in Figure 4.

We explore the fraction of variable AGNs as a function of
galaxy and light-curve properties. Uncertainties are binomial
limits computed following Gehrels (1986). In Figure 5, we
show the fraction of variability-selected AGNs as a function of
galaxy host stellar mass; we find that the AGN fraction
increases toward higher stellar masses. In Figure 6, we show
histograms of stellar mass for the full sample and for variable
AGNs. The sample of variable AGNs skews toward higher
stellar masses; the median stellar mass of the overall sample is
$4.5 \times 10^9 M_{\odot}$, while the median stellar mass of the variability-
selected AGN is $8.3 \times 10^9 M_{\odot}$. The pink shaded region in
Figures 5 and 6 denote the region $M_*=2 \times 10^{10} M_{\odot}$, where
our sample is incomplete in stellar mass.

The decline in variability fraction toward low stellar masses
cannot be taken at face value. As we show in the top panel of
Figure 7, the AGN fraction is also a strong function of the
nucleus apparent magnitude. Additionally, Figure 3 showed
that the scatter in a given light curve increases as the nucleus
magnitude gets fainter, so the lower variability fraction for

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### Table 2

| Category           | $N_{\text{galaxies}}$ | Variable AGN (%) |
|--------------------|----------------------|------------------|
| Overall            | 47,125               | 0.9 ± 0.05       |
| $M_* > 10^{10} M_{\odot}$ | 12,052              | 1.5 ± 0.15       |
| $M_* < 10^{10} M_{\odot}$ | 35,073              | 0.7 ± 0.06       |
| BPT AGN/Comp       | 8355                 | 1.7 ± 0.2        |
| BPT SF             | 28749                | 0.6 ± 0.06       |
| Broad-line AGN     | 249                  | 27.7 ± 4.0       |
| Baseline < 2 yr    | 6854                 | 0.25 ± 0.09      |
| Baseline > 2 yr    | 40,139               | 1.0 ± 0.05       |

**Note.** Variability percentages for different subsamples. These reflect the number of variable AGNs in each sub-sample divided by the total number of objects in that sample. The BPT AGN and SF classes are based on the emission-line strengths reported in the NSAv0. Uncertainties are binomial limits for a 90% confidence level (Gehrels 1986).

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lower-mass galaxies could be due to the fact that the lower-mass galaxies are fainter. We address this further in Section 6.

In Figure 8, we show the fraction of variable AGNs as a function of the light-curve baseline, for the full sample, as well as for narrow-line AGNs and narrow-line star-forming objects. For the overall sample, the fraction of variable AGNs increases from 0.25% ± 0.09% for light curves shorter than 2 yr to 1% ± 0.05% for light curves longer than 2 yr. For narrow-line AGNs, the variable fraction reaches 2.5% for baselines longer than 6 yr. Especially as data from LSST begins to come in, any estimate of the variable AGN fraction for a population should take into account the baseline over which it is being measured.

Figure 3. Light-curve standard deviation vs. PTF R-band nuclear magnitude. The shaded gray contours show the full population of galaxies from the NSAv0. The blue circles show galaxies we identify as having AGN-like variability. The orange points show the variable AGN from our ancillary samples (described in Section 2.2). The typical scatter in a light curve increases toward fainter galaxy nuclei.

Table 3
237 Low-mass Galaxies with AGN-like Variability

| NSA ID      | R.A.  | Decl. | Redshift | Stellar mass (log₁₀(M*)-0.5) | Npoints | Baseline (days) | Median mR (mag) | Std. dev. | σ var | σ QSO | σ notQSO |
|-------------|-------|-------|----------|-------------------------------|---------|----------------|-----------------|------------|-------|-------|----------|
| NSA126546   | 4.29825 | 29.4809 | 0.0235 | 9.99                          | 209     | 1546.75        | 17.16           | 0.014     | 2.65  | 2.47  | 0.04     |
| NSA126631   | 4.65217 | 29.93285 | 0.0215 | 9.84                          | 154     | 1546.75        | 17.68           | 0.024     | 6.52  | 4.09  | 0.18     |
| NSA23643    | 10.19812 | 0.62188 | 0.0414 | 9.84                          | 153     | 1863.94        | 17.58           | 0.019     | 2.8   | 2.34  | 0.11     |
| NSA5956     | 13.79728 | −0.77002 | 0.0425 | 9.98                          | 107     | 1551.92        | 17.45           | 0.026     | 7.96  | 3.31  | 1.19     |
| NSA128247   | 14.97201 | 31.82702 | 0.0149 | 9.9                            | 59      | 1540.92        | 15.3            | 0.125     | 166.16| 10.86 | 8.73     |
| NSA44590    | 16.44724 | 0.50798 | 0.05   | 9.33                          | 131     | 1551.88        | 18.83           | 0.041     | 4.08  | 2.08  | 0.85     |
| NSA62320    | 20.6387 | 0.13574 | 0.0441 | 9.15                          | 282     | 1506.02        | 19.46           | 0.059     | 8.21  | 3.62  | 0.9      |
| NSA129568   | 21.40065 | 34.73646 | 0.0162 | 9.83                          | 264     | 1458.15        | 16.2            | 0.012     | 7.03  | 6.45  | 0.0      |
| NSA8747     | 22.22581 | 14.9397 | 0.0332 | 9.34                          | 23      | 1180.06        | 18.19           | 0.047     | 6.46  | 2.67  | 0.96     |
| NSA9053     | 27.32894 | 13.04779 | 0.0178 | 9.72                          | 238     | 1867.07        | 16.93           | 0.016     | 8.74  | 8.04  | 0.0      |
| NSA44431    | 27.4215 | 0.89644 | 0.0244 | 8.84                          | 49      | 1533.73        | 19.48           | 0.058     | 2.55  | 2.63  | 0.11     |

Note. Variability-selected AGNs with M* < 10^{10} M_☉, in order of R.A. NSA ID refers to the ID given in the NSAv0. σ var, σ QSO, and σ notQSO refer to the significance that the given light curve is variable, an AGN, or a false alarm, respectively. Details on these parameters can be found in Section 3.2. A full version of this table is available in the online version.

(This table is available in its entirety in machine-readable form.)
Figure 4. Three low-mass galaxies with star formation-dominated narrow emission lines and AGN-like variability. These galaxies span from \(5 \times 10^7\) to \(2 \times 10^9\) \(M_\odot\) in stellar mass. The images cutouts (left) are from the DECaLS Legacy Survey browser and are 30″ on each side. The black circles are the measured PTF \(R\)-band magnitude values measured within a 3″ nuclear aperture. The light curves (right) give the PTF \(R\)-band nucleus magnitudes over 5.5 yr. In the light curves, the gray circles are data, the blue line represents the best-fit damped random walk model, and the shaded blue region shows the range of model uncertainties.
4.1.1. Spectroscopic Properties

SDSS spectra are available for 357 of the 417 galaxies with AGN-like variability. The galaxies without SDSS spectra have spectroscopic redshifts available from other databases, and we do not analyze their spectra here. In Figure 9, we show where the variability-selected AGNs from the NSAv0 fall on the BPT diagram. We found that 84 galaxies could not be placed on the BPT diagram, as one or more of the relevant lines were absorption-dominated. Of the 273 galaxies on the BPT diagram, 40% are in the AGN/composite regions, and 60% are in the star-forming region.

The high fraction of variable AGNs in the star-forming region is driven by the fact that our sample is dominated by low-mass galaxies. Among galaxies with $M_*>10^{10} M_\odot$, 70% are in the AGN/composite regions; for galaxies with $M_*<10^{10} M_\odot$, 25% are in the AGN/composite region. There are also 35 galaxies with broad Hα emission, roughly two-thirds of which have $M_*>10^{10} M_\odot$. Two of the 35 broad Hα galaxies fall in the star-forming region of the BPT diagram; the remainder are in the composite or AGN regions.

Figure 5. Fraction of variability-selected AGNs vs. galaxy stellar mass for the main NSA sample. The red shaded region shows the mass range where our sample is incomplete; galaxies in this region correspond to the serendipitous NSA galaxies. The number above each point gives the total number of galaxies in that mass bin. The error bars are the binomial limits for a 90% confidence level (Gehrels 1986).

Figure 6. Normalized histograms of the stellar mass distribution of the main NSAv0 sample (gray), and galaxies with AGN-like variability (light blue). The red shaded region shows the mass range where our sample is incomplete; galaxies in this region correspond to the serendipitous NSA galaxies.

Figure 7. Top: the fraction of variable AGNs vs. the nucleus PTF R-band magnitude. Bottom: fraction of variable AGNs vs. galaxy absolute g-band magnitude from the NSAv0.
Galaxies with AGNs could fall in the star-forming region of the BPT diagram due to star formation dilution of the AGN signal within the SDSS spectroscopic fiber or due to low-metallicity. As shown in Groves et al. 2006, galaxies with subsolar metallicity would lie in the upper left region of the diagram ($\log_{10}([\text{N II}]/H\alpha) < -1.0$ and $\log_{10}([\text{O III}]/H\beta)$ ranging from $\sim 0.25$ to 1.0). We find a handful of galaxies in this regime; these tend to be some of the lowest-mass galaxies in our variable sample. The fraction of galaxies with AGN-like variability with SDSS optical spectroscopy dominated by star formation demonstrates that particularly at low galaxy stellar masses, AGN selection via photometric variability can find AGNs that would be missed by standard optical spectroscopic selection techniques.

4.2. Broad-line AGN

We are interested in exploring trends between variability properties and BH mass. Within our NSA sample, we use the Liu et al. (2019) list of broad-line AGNs to identify 57 broad-line AGNs. To augment this sample, we additionally extract light curves from 192 broad-line AGNs from Greene & Ho (2007) and Reines & Volonteri (2015). This gives a final count of 249 broad-line AGNs for which we analyze PTF light curves. Overall, we find that 69/249 objects show AGN-like variability (28%).

In Figure 10, we show the variable fraction as a function of baseline for broad-line AGNs. For baselines of 2500 days, almost 40% of broad-line AGNs are found to be variable, compared to $\sim 20\%$ for light curve baselines of $\sim 500$ days. We
also plot the variability fraction as a function of the BH mass, and find that the fraction remains roughly constant with BH mass. This suggests that, at least down to BH masses of $\sim 10^5 M_\odot$, the presence of AGN variability is not dependent on the mass of the central BH.

Using this sample, we also explore possible relations between BH mass and variability properties. While possible relations between variability and AGN luminosity, Eddington ratio, and BH mass have been studied (Wold et al. 2007; MacLeod et al. 2010; Zuo et al. 2012; Caplar et al. 2017), the field has not reached a consensus. Here, we search for relations between BH mass and damped random walk parameters. A damped random walk (also known as an Ornstein–Uhlenbeck process) with noise has parameters $\mu$, $\sigma$, $\tau$, and $\omega$, where $\mu$ is the long-term mean, $\tau$ is a reversion timescale, $\sigma$ represents the instantaneous variability amplitude, and $\omega$ is the noise amplitude. These parameters can be estimated using the maximum-likelihood estimator. We estimate $\mu$, $\sigma$, $\tau$, and $\omega$ using the logarithmic likelihood function given in Holý & Tomanová (2018; see their Equations (28) and (29)).

When fitting AGN light curves with a damped random walk, it is common to report the “structure function at infinity” ($SF_\infty$); this quantity is a function of the reversion timescale $\tau$ and instantaneous variability amplitude $\sigma$ as $SF_\infty = \sigma \tau^{1/2}$, and can be thought of as an asymptotic variability amplitude. Figure 11 shows light curves of two broad-line AGNs and their estimated DRW parameters.

We estimate $\tau$ and $SF_\infty$ for the variable broad-line AGNs from the samples listed above. Of 69 broad-line variable AGNs, $\tau$ and $SF_\infty$ are well-constrained for 52 of them. We find values of $\tau$ ranging from 8 days to 600 days (median $\tau = 67$ days) and $SF_\infty$ ranging from 0.01 to 0.2 mag (median $SF_\infty = 0.04$ mag). We then search for dependencies of $\tau$ and $SF_\infty$ on BH mass and nucleus luminosity. In Figure 12 we show absolute nucleus R-band magnitude versus BH mass, with points color-coded by values of $SF_\infty$ and $\tau$. We do not find statistically significant correlations between either $\tau$ or $SF_\infty$ and the BH mass and nucleus luminosity. However, we note that qualitatively, objects with the highest $SF_\infty$ are those with the highest BH masses in our sample, and that the objects with the
shortest reversion timescales have lower BH masses. This is in good agreement with results from MacLeod et al. (2010), though a larger sample is needed to further explore dependencies between DRW parameters and BH properties. Note that nucleus magnitude includes both the AGN and the underlying stellar population within 3″.

5. AGN-like Variability in Low-mass Galaxies

We find 237 galaxies with AGN-like variability and stellar masses below 10^{10} M_☉. Here, we discuss the origin of the variability and compare the population of AGNs detected in low-mass galaxies via long-term variability to those detected with other techniques. We also discuss our results in the context of the low-mass end of the BH occupation fraction.

5.1. Origin of Variability

Sources of optical photometric variability include stellar processes, tidal disruption events, and AGNs. To guard against contamination from supernovae, any objects meeting the DRW criterion but exhibiting burst-like variability were removed from the sample of AGNs. In addition to supernovae, another potential stellar contaminant is luminous blue variable stars (LBVs). Though LBVs can have bolometric luminosities as bright as 10^{39} erg s^{-1} (Smith et al. 2011), most will be too faint to be a contaminant for our targets. Soraisam et al. (2020) studied the variability of massive stars in M31 with PTF/iPTF. The LBVs in their M31 sample range in apparent PTF R-band magnitude from 16 to 22; these would generally not be detectable at the distances of the galaxies in our sample. Bright LBVs such as the LBV in η Carinae have episodic mass-loss and show high-amplitude optical variability (up to 1 mag). These also typically show broad Balmer emission lines with P Cygni absorption components. We do not observe P Cygni profiles in the spectra of any of the variability-selected AGNs. Thus, we do not expect LBVs to be potential contaminants for the majority of our variability-selected AGN hosts.

In Figure 13, we show the reduced χ^2 value for a non-AGN variable versus the reduced χ^2 for the DRW model for the underlying sample and for each variability-selected AGN. Per our selection criteria, all of the variability-selected AGNs have DRW reduced χ^2 values which are lower than the reduced χ^2 for a non-AGN variable. Note that objects with AGN-like variability and SF-like narrow emission lines occupy the same region of parameter space as those with AGN or composite BPT classifications. They also occupy the same region as variable broad-line AGNs. We conclude that AGN variability is the most likely explanation for the variable light curves that are well-described by a DRW model, including those corresponding to
5.2. Comparison to Other Selection Techniques

Most AGNs in low-mass galaxies have been identified through optical spectroscopic selection techniques (Greene & Ho 2004, 2007; Reines et al. 2013; Moran et al. 2014). Reines et al. (2013) identified 136 dwarf galaxies in the NSAv0 (defined as galaxies with stellar masses less than the Large Magellanic Cloud, or $M_\star < 3 \times 10^9 M_\odot$) with narrow emission lines consistent with the presence of an AGN based on the BPT diagram (Baldwin et al. 1981). Of the 136 galaxies with narrow-line evidence for an AGN, 10 also had broad emission lines. All galaxies in Reines et al. (2013) are contained within our main NSA sample, since they meet our initial mass selection. We are able to construct PTF light curves with more than 20 data points for 66 out of 136. We find 2/66 have AGN-like variability: NSA 15235 and NSA 118505 (RGG 32 and RGG 91, respectively, in Reines et al. 2013). NSA 15235 has broad Hα emission and narrow emission lines in the AGN region of the BPT diagram, while NSA 118505 has no detectable broad line in SDSS and narrow emission lines in the AGN region of the BPT diagram. The broad emission line in NSA 15235 gives a BH mass of $M_{\rm BH} \approx 1.5 \times 10^5 M_\odot$. Light curves for these objects are shown in Figure 14.

The overall variable fraction for the Reines et al. (2013) narrow-line AGN is $3 \pm 2\%$ (90% confidence limits), consistent with the variable of AGN among all narrow-line AGN/composites in our main NSA sample (1.7% ± 0.2%). AGN variability in dwarf galaxies with AGN-dominated narrow emission lines is thus consistent with what is found for higher-mass systems.

We now compare the fractions of AGNs in dwarf galaxies discovered via optical spectroscopy versus AGN variability. There are 44594 galaxies with stellar masses less than $3 \times 10^9 M_\odot$ in the NSAv0: 136 have evidence for an AGN based on the BPT diagram (Reines et al. 2013). This gives an active fraction based on optical spectroscopy of 0.3% ± 0.05%. For the same mass range ($M_\star < 3 \times 10^9 M_\odot$), we find 102 objects with AGN-like variability, out of 18,251. This gives a variability-based active fraction of 0.56% ± 0.07%. There is only a small amount of overlap between the two samples, as only two of our variability-selected AGNs in this mass regime are also identified as AGNs in Reines et al. (2013). Variability is thus identifying a complementary population of AGNs in low-mass galaxies as compared to optical spectroscopic selection.

Recent work by Birchall et al. (2020) studies the optical spectroscopic properties of X-ray selected AGNs in dwarf galaxies. Using X-ray data from XMM-Newton, they search for X-ray emission from a parent sample of ~4000 galaxies with $z \leq 0.25$. Of the 61 dwarf galaxies they identify with X-ray evidence for an AGN, more than 80% fall in the star-forming region of the BPT diagram, providing further support for the idea that BPT selection may miss AGNs in low-mass systems.

As discussed above, star formation dilution and/or metallicity effects could be responsible the variability-selected AGN falling primarily in the star-forming region of the BPT diagram. In Figure 15, we compare the galaxy $g-r$ colors for variability-selected AGNs to the Reines et al. (2013) AGNs. The variability-selected AGNs tend to be bluer than the Reines et al. (2013) AGN host galaxies (median $g-r = 0.33$, compared to 0.5 for the Reines et al. 2013 AGNs), which lends support to the star formation dilution hypothesis. In some cases, isolating emission from the nucleus with higher spatial resolution spectroscopy reveals a change in the narrow-line ratios toward the AGN region of the BPT diagram (e.g., Dickey et al. 2019). Spatially resolved spectroscopy of the variability-selected low-mass AGNs will reveal whether star formation dilution is indeed responsible for the star formation-dominated SDSS spectra.

Another intriguing possibility is that many of the observed AGNs in dwarf galaxies come from the tidal disruption of stars. As discussed in Zubovas (2019), feeding BHs in dwarf galaxies with inflowing gas streams is difficult due to stellar feedback, but the population of AGNs in dwarf galaxies could be explained by tidal disruption events (TDEs) if the occupation fraction is close to 1. There is some recent evidence for accretion disk formation in at least some TDEs (e.g., Wevers et al. 2019a). If the detected variability is from recently formed accretion disks, this would also help explain the lack of narrow emission-line signatures in many of the low-mass variability-selected AGNs, as the narrow-line region can extend to a
The Astrophysical Journal, 896:10 (13pp), 2020 June 10

Baldassare, Geha, & Greene

kiloparsec or farther. Less inflowing gas in the vicinity of the BH (as compared to AGN in more massive galaxies) could also explain the lack of strong broad and/or narrow AGN emission-line signatures. Interestingly, Wevers et al. (2019b) studied the optical spectra of the host galaxies of ∼25 optical and X-ray TDEs and found that the majority of hosts were either quiescent or had narrow emission lines consistent with star formation.

5.3. Implications for the Occupation Fraction

The occupation fraction is defined as the fraction of galaxies containing a central BH. Dynamical BH detections in nearby galaxies have revealed that the occupation fraction is ∼100% for galaxies with stellar masses greater than 10^9 M_☉. The occupation fraction for systems with M_☉ < 10^9 M_☉ remains relatively unconstrained, though recent estimates place it between 30% and 90% (Miller et al. 2015; Nguyen et al. 2018, 2019). At face value, the drop in the fraction of variable AGNs toward low stellar masses suggests a lower occupation fraction for galaxies below 10^9 M_☉. However, as demonstrated by Figure 3, lower levels of fractional variability are more detectable in brighter nuclei. In order to compare high- and low-mass galaxies, we first must correct for differing magnitude distributions. Note that the typical baseline and number of data points for galaxies above and below 10^9 M_☉ are consistent with one another.

From our main NSAv0 galaxy sample, we find the variable AGN fraction for galaxies with M_☉ > 10^10 M_☉ is 1.5% ± 0.17 (90% confidence limits). We next consider the population between 10^9 and 10^10 M_☉. Since the high- and low-mass samples have different apparent magnitude distributions, we create a weighting function equal to the ratio of the magnitude probability distributions for the high- and low-mass samples. We then assign weights to each galaxy in the low-mass sample, and draw a random population that matches the magnitude distribution of the high-mass sample. We draw 1000 subsamples in this manner and use the results to compute the median number of variability-selected AGNs in the low-mass sample. Figure 16 shows an example of the magnitude distributions, demonstrating that the magnitude distribution of one instance of the low-mass subsample matches the magnitude distribution of the high-mass sample. We also repeat these steps for the sample of galaxies with M_☉ < 10^9 M_☉.

We find that the magnitude-matched fraction of variable AGNs for galaxies with stellar masses from 10^9 to 10^10 M_☉ is 1.4% ± 0.4 (90% confidence limits). Within the uncertainties, this is consistent with the fraction of variable AGNs in higher-mass galaxies. Given that there do not appear to be differences in variability properties with BH mass, this suggests that the local occupation fraction between 10^9 and 10^10 M_☉ is not substantially lower than the occupation fraction above M_☉ > 10^10 M_☉. This is consistent with results based on dynamical detections of BHs in very nearby, low-mass early-type galaxies (Nguyen et al. 2018, 2019).

For the lowest-mass bin (M_☉ < 10^9 M_☉), we find a variability fraction of 0.6% ± 0.4. This is inconsistent with the fraction of variable AGNs in galaxies with M_☉ > 10^9 M_☉, even after accounting for different magnitude distributions. This could reflect a lower occupation fraction, but could also be due to incompleteness in the NSAv0 for galaxies with M_☉ < 10^9 M_☉, or to these galaxies hosting BHs that are below our detection thresholds. Larger and deeper samples will be needed to place meaningful constraints on the active fraction for M_☉ < 10^9 M_☉. However, there are presently no constraints on the occupation fraction in this mass regime, so identifying any galaxies with AGNs in this mass regime represents a step forward.

6. Summary and Future Directions

We analyze light curves of 47,125 nearby (z < 0.055) galaxies from the NASA–Sloan Atlas with Palomar Transient Factory coverage with the goal of identifying variable AGN in low-mass galaxies. Our sample is complete for stellar masses less than M_☉ = 2 × 10^10 M_☉, but extends up to stellar masses of 10^{12} M_☉. Our key results are summarized below.

1. We find 417 galaxies with AGN-like variability, 237 of which have stellar masses less than 10^{10} M_☉.
2. Of the low-mass galaxies identified as having AGN variability, 75% have narrow emission lines dominated by star formation, and thus would be missed in optical spectroscopic searches. This could be due to star formation dilution, low galaxy metallicity, or a difference in primary AGN fueling mechanisms for low-mass galaxies.
3. Low-mass, variability-selected AGNs reside in bluer host galaxies than those selected by optical spectroscopy, with little overlap between variability and BPT-selected AGNs (Section 6.1). This suggests at least some of the variability-selected AGNs may be undetected in SDSS spectroscopy due to star formation dilution.
4. The fraction of variable AGNs is constant down to M_☉ ≈ 10^9 M_☉, suggesting that the occupation fraction does not change drastically in this mass regime (Section 6.2). This is in good agreement with recent occupation fraction results from Miller et al. (2015) and Nguyen et al. (2018, 2019).
5. Below M_☉ = 10^9 M_☉, the fraction of variable AGNs drops. It is not clear whether this is due to a change in

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**Figure 15.** Histogram of galaxy g − r colors for optical spectroscopic-selected AGN in dwarf galaxies (M_☉ < 3 × 10^9 M_☉) from Reines et al. (2013) and PTF variability-selected AGNs in the same mass range. PTF-variable AGNs are shown in blue and Reines et al. (2013) is shown in purple. The blue and purple dashed lines represent the median g − r for the PTF sample and Reines et al. (2013) sample, respectively. The Reines et al. (2013) AGNs are, on average, in redder galaxies than the variability-selected AGNs.
occurrence fraction or incompleteness. Larger samples and deeper repeat imaging surveys are needed to place meaningful constraints on the active fraction below stellar masses of $10^9 M_\odot$.

6. The measured AGN fraction is strongly dependent on measurement baseline. The AGN fraction for baselines less than two years is 0.25%, compared to 1% for baselines longer than two years.

7. We find no significant correlations between BH mass and the reversion timescale or variability amplitude for a sample of 52 broad-line AGNs with single-epoch spectroscopic BH masses ranging from $10^5$–$10^8 M_\odot$.

The PTF survey has recently been superseded by the Zwicky Transient Facility (Graham et al. 2019), which has similar imaging quality and resolution, but uses a much larger CCD, facilitating faster coverage of the full sky. Future analysis will incorporate data from the ZTF survey, allowing us to study AGN variability on even longer timescales with shorter cadences. Additionally, LSST, which will image the entire visible night sky every three nights and is expected to come online in the next few years, will be an incredible resource for identifying low-mass AGN via optical variability (Ivezic et al. 2008).

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