Optical Variability of Quasars with 20-Year Photometric Light Curves

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ABSTRACT

We study the optical gri photometric variability of a sample of 190 quasars within the SDSS Stripe 82 region that have long-term photometric coverage during ~1998–2020 with SDSS, PanSTARRS-1, the Dark Energy Survey, and dedicated follow-up monitoring with Blanco 4m/DECam. With on average ~200 nightly epochs per quasar per filter band, we improve the parameter constraints from a Damped Random Walk (DRW) model fit to the light curves over previous studies with 10–15 yr baselines and ≤100 epochs. We find that the average damping timescale $\tau_{\text{DRW}}$ continues to rise with increased baseline, reaching a median value of ~750 days ($g$ band) in the rest-frame of these quasars using the 20-yr light curves. Some quasars may have gradual, long-term trends in their light curves, suggesting that either the DRW fit requires very long baselines to converge, or that the underlying variability is more complex than a single DRW process for these quasars. Using a subset of quasars with better-constrained $\tau_{\text{DRW}}$ (less than 20% of the baseline), we confirm a weak wavelength dependence of $\tau_{\text{DRW}} \propto \lambda^{0.51\pm0.20}$. We further quantify optical variability of these quasars over days to decades timescales using structure function (SF) and power spectrum density (PSD) analyses. The SF and PSD measurements qualitatively confirm the measured (hundreds of days) damping timescales from the DRW fits. However, the ensemble PSD is steeper than that of a DRW on timescales less than ~a month for these luminous quasars, and this second break point correlates with the longer DRW damping timescale.

Key words: surveys – quasars: general – quasars: supermassive black holes

1 INTRODUCTION

The optical photometric (continuum) variability of quasars encodes critical information about physical processes within the accretion disk of a rapidly accreting supermassive black hole (SMBH) that primarily emits in the rest-frame UV through optical. There has been significant progress in the past few decades in quantifying the observed optical variability of quasars with increasing sample sizes and light curve quality (e.g., Giveon et al. 1999; Hawkins 2002; Vanden Berk et al. 2004; de Vries et al. 2005; Sesar et al. 2006; Bauer et al. 2009; MacLeod et al. 2010, 2012; Sun et al. 2014; Morganson et al. 2014; Kasliwal et al. 2015; Chen & Wang 2015; Simm et al. 2016; Caplar et al. 2017; Smith et al. 2018; Sánchez-Sáez et al. 2018; Li et al. 2018; De Cicco et al. 2019; Luo et al. 2020; Tachibana et al. 2020; Laurenti et al. 2020; Xin et al. 2020; Suberlak et al. 2021). However, the nature of optical variability of quasars is still poorly understood (e.g., Ulrich et al. 1997; Padovani et al. 2017).

Quasars are observed to vary stochastically over a broad range of timescales and wavelengths. In the rest-frame UV-optical, quasar variability amplitude increases with timescales and decreases with wavelength (e.g., Vanden Berk et al. 2004), and is observed to anticorrelate with luminosity and the Eddington ratio of the quasar (e.g., Ai et al. 2010; Rumbaugh et al. 2018). On months to years timescales, quasar optical variability typically saturates at the ~10–20% level. Traditionally, the characterization of quasar variability has been carried out with the structure function (SF) or power spectrum density (PSD) measurements, which quantify the variability level as a function of timescale (or frequency).
It has become increasingly popular in recent years to model quasar light curves in the time domain with stochastic processes (e.g., Kelly et al. 2009; Koźłowski et al. 2010; Kelly et al. 2014). This approach addresses concerns of sampling and windowing effects that come with time series analyses in the frequency domain, which are particularly relevant for ground-based quasar light curves. The Damped Random Walk (DRW) model has emerged as the simplest Gaussian random process model that can fit the optical light curves of quasars reasonably well (e.g., Kelly et al. 2009; Koźłowski et al. 2010; MacLeod et al. 2010). Deviations from the DRW model have been reported (e.g., Mushotzky et al. 2011; Zu et al. 2013; Kasliwal et al. 2015; Guo et al. 2017), although some of these claims are likely impacted by the limited duration of the light curve in the DRW fit (e.g., Koźłowski 2017). More complex stochastic process models, such as the continuous auto-regressive moving-average (CARMA; Kelly et al. 2014) models, can accommodate a broader range of PSD shapes, and improve the fits provided that the light curve quality is sufficiently high. In general the CARMA models do not have to be solutions to the stochastic differential equation driven by a Gaussian process (i.e., a Wiener process). However, for CARMA processes that are Gaussian, the model parameters can be estimated using efficient implementations of Gaussian process regression (e.g., Foreman-Mackey et al. 2017; Yu & Richards 2022). In this work we focus on CARMA processes that are Gaussian.

In the DRW model, the PSD is described by a $f^{-2}$ power-law at the high-frequency end, transitioning to a white noise at the low-frequency end. The transition frequency $f_0$ corresponds to the damping timescale $\tau_{DRW}$ as $f_0 = 1/(2\pi\tau_{DRW})$. The damping timescale thus describes a characteristic timescale of the optical variability. Earlier studies of quasar variability already hinted at such a characteristic variability timescale and its possible dependence on the physical properties of quasars such as the black hole mass (e.g., Collier & Peterson 2001; Kelly et al. 2009), but the exact form of the dependence is debated (e.g., MacLeod et al. 2010; Simm et al. 2016). Recently, Burke et al. (2021) measured the damping timescales using the DRW model for a sample of Active Galactic Nuclei (AGNs) with high-quality optical light curves over a large dynamic range in black hole mass. They found a strong positive correlation between $\tau_{DRW}$ and black hole mass, which extends to the stellar mass regime with optical variability measured for nova-like accreting white dwarfs (Scaringi et al. 2015). Compared with higher-order Gaussian process models, the DRW model contains a single characteristic timescale, making it easier to interpret the variability and to connect variability to the underlying physical processes (e.g., Burke et al. 2021; Sun et al. 2020).

However, as Koźłowski (2017) pointed out, in order to constrain the damping timescale $\tau_{DRW}$ when fitting the light curve with a DRW model, it is important that the duration of the light curve is substantially longer than $\tau_{DRW}$. For light curves shorter than a few times $\tau_{DRW}$, the measured $\tau_{DRW}$ values may be systematically biased low and saturated around 20–40% of the light curve duration, with elevated scatter in the measurements. Many of the DRW fits to SDSS Stripe 82 quasars in MacLeod et al. (2010) do not pass this duration test, and their reported $\tau_{DRW}$ values may be underestimated. Suberlak et al. (2021) extended the Stripe 82 light curves by another 5 years using the PanSTARRS-1 (PS1) data (Chambers et al. 2016), which alleviated this problem. But many of the updated $\tau_{DRW}$ measurements are still not short enough compared with the baseline. In addition, the number of PS1 epochs is small compared with the SDSS data, and the DRW fits are likely still dominated by the SDSS light curves.

The main purpose of this work is to study optical continuum variability of a sample of quasars with a more extended 20-yr baseline. This sample represents one of the best-quality light curve data sets to study quasar variability, with hundreds of epochs from SDSS, PS1 and the high-cadence/high-S/N monitoring from the Dark Energy Survey, as well as our dedicated follow-up photometric monitoring with DECam on the CTIO-4m Blanco telescope. We will improve the DRW measurements using these extended light curves and quantify the general optical variability properties with SF and PSD analyses.

This paper is organized as follows. In §2 we describe the sample and the photometric light curve data. In §3 we present our variability measurements, with the technical details provided in Appendix A. We discuss the implications of our results in §4 and conclude in §5. Throughout this paper we adopt a flat $\Lambda$CDM cosmology with cosmological parameters $\Omega_M,0 = 0.3$ (\Omega_{\Lambda,0} = 0.7) and $H_0 = 70\text{km}\text{s}^{-1}\text{Mpc}^{-1}$. By default all timescales are in the rest-frame of the quasar unless otherwise specified; in cases where ambiguity may arise in the context we use subscripts "rest" and "obs" to explicitly refer to rest-frame and observed-frame timescales.

## 2 DATA

To study optical quasar variability with long-term light curves, we utilize quasars identified in the SDSS Stripe 82 region (S82), a nearly 300 deg$^2$ stripe along the celestial equator, imaged by SDSS from ~1998 to 2007. S82 was repeatedly observed to find supernova, being one of the most frequently observed areas in SDSS. Each target within S82 was repeatedly observed for an average of 60 epochs, albeit aperiodically and with large time gaps, as the observing window spanned 2-3 months each year. SDSS photometry has five bandpasses ([gri]SDSS) available for each quasar, allowing for the study of variability as a function of wavelength. The SDSS light curves in S82 provide an initial 10-year baseline for quasar variability studies (e.g., MacLeod et al. 2010). To extend this baseline, we use data from PS1 (Chambers et al. 2016) spanning nearly 5 years during 2010-2014. PS1 imaged the sky in the ([gri]PS1) bandpasses with ~ 2 epochs per year in its wide-area survey. The combined SDSS+PS1 light curves for S82 quasars have a baseline of ~ 15 yrs, and were used to study quasar variability in Suberlak et al. (2021) to improve the DRW fits. However, there were only a handful of PS1 epochs, and the DRW fits were potentially dominated by the SDSS data.

To extend our baseline further, we use data from the DES survey during 2013-2019, which imaged the sky in the ([gri]DES band-
pass. In particular, among the repeatedly observed DES Transient Survey (Deep) Fields (Hartley et al. 2022), there were two in the S82 region (SN-S1 and SN-S2, centered at J2000 coordinates 02:51:16.8+00:00:00:0 and 02:44:46.7−00:59:18.2, respectively), each with 2.7 deg² area, with > 100 epochs in each band over six years. The light curves in different bands have similar cadences, but are not necessarily simultaneous (i.e., on the same nights). After DES completed its wide field survey in 2019, we continued to monitor these two S82 DES-deep fields with a dedicated long-term program (2019-2024) using the DECam imager on the CTIO-4m telescope (NOAO program 2019B-0219; PI: X. Liu) to extend the baseline further in 3 bands (gri)DES.

In this work we use the combined light curve data from SDSS, PS1, DES and DECam imaging for 190 spectroscopically confirmed quasars in SDSS that are within the two DES-deep fields in S82 (Fig. 1 and Fig. 2). These quasars are all within the SDSS DR7 quasar catalog, with derived physical properties such as bolometric luminosities and black hole masses from Shen et al. (2011). Our combined baseline is ~20 yrs, enabling a detailed quasar variability study over decades-long timescales. The inclusion of the DES and DECam imaging is of critical importance: it not only extends the baseline by another 6 years to improve the constraints on the damping timescale, but also provides a large number of high-S/N epochs to sample days to years timescales and to ensure the DRW fits are not dominated by the SDSS epochs.

All of these quasars have observations in the gri bands for all surveys, so we focus on these three bands for multi-wavelength variability. Although z-band data are also available across most of these surveys, the variability amplitude in this red band is lower and host contamination would be more significant, thus complicating the quasar variability measurements. We model the light curves in each band separately, instead of fitting the multi-band light curves simultaneously as did in Hu & Tak (2020). The latter approach may be useful to further constrain inter-band correlations of the light curves.

We obtain public SDSS light curve data for each of these quasars from the catalog curated in MacLeod et al. (2012), which provides light curves for nearly 9000 SDSS S82 quasars in all five ugriz bandpasses. We obtain public PS1 photometry for each quasar using the MAST database (https://archive.stsci.edu/), querying for all gri bands and excluding detections with low confidence. The proprietary DES data and our dedicated DECam imaging data are processed with the same DES pipeline (Morganson et al. 2018). We use PSF magnitudes from all these surveys for our quasars.

The filter bandpasses differ slightly between SDSS, PS1, and DES, and we apply photometric offsets to obtain merged light curves in a common bandpass for each quasar. Photometric offsets are typically

**Figure 2.** The distribution of 190 SDSS S82 quasars in our sample in the bolometric luminosity versus redshift plane. The individual targets are color-coded by their intrinsic rms variability in the g-band ($\sigma_{g, r}$), calculated using a maximum-likelihood approach described in Shen et al. (2019). The gray contours behind the data points represent the distribution of $L_{bol}$ and $z$ from ~100,000 SDSS DR7 quasars (Shen et al. 2011), which are on average brighter than SDSS quasars selected in the S82 region.

**Figure 3.** Histograms of the photometric offsets used for each target in each survey. The top row represents offsets from PS1 bands to SDSS bands, and the bottom row represents offsets from the combined PS1/SDSS bands to DES bands. The three columns represent the gri bands in corresponding order from left to right. The dashed lines represent 0.01 and 0.1 mag corrections for each band.

**Figure 4.** Example light curves from our quasar sample. These light curves are taken over a ~20 year baseline, across different surveys. To adjust the observed magnitudes in a common band, we apply empirical color offsets and additional small (~0.05 mag) offsets to merge the light curves. The data for all light curves are provided in the FITS table described in Table 1.
constructed using colors of objects rather than magnitudes themselves, as these colors are less variable. We choose to use the mean color-based offsets described in Liu et al. (2016) to offset PS1 data into the corresponding SDSS bands, and then use the offsets described in Drlica-Wagner et al. (2018) to offset both SDSS and PS1 magnitudes into the corresponding DES bandpasses. Fig. 3 shows that most of the corrections between surveys lie under 0.1 mag for each band. PS1 \(ri\) magnitudes are sufficiently similar to SDSS \(ri\) magnitudes so that no correction is needed, but we opt to do so for a similar processing of all bands. All other bandpasses for each survey have small offsets, with only a handful of objects with offsets up to 0.3 mag. Therefore, the use of these mean color photometric offsets is justified for our sample.

After correcting for the zero-point offset in the same bandpass, we find that the \(r\)- and \(i\)-band light curves still display a small offset between the overlapping PS1 and DES epochs for some quasars. This additional offset is likely due to the usage of PSF magnitudes, extended host galaxy emission, seeing variations between PS1 and DES observations, as well as any residual systematics between surveys. We therefore apply an additional correction (~ 0.05 mag) to manually bring the overlapping PS1 and DES epochs into agreement. We have tested w/ and w/o this minor magnitude offset between PS1 and DES and found that this detail has no effect on our variability analyses.

We show a few representative examples of the merged light curves from SDSS+PS1+DES+DECam in Fig. 4. We summarize the basic properties of our quasar sample in a FITS table along with the best-fit DRW parameters, where we compile additional properties of these quasars from the catalog in Shen et al. (2011). The columns of this FITS table are described in Table 1. We also provide all light curve data in the FITS table described in Table 1.

3 RESULTS

3.1 DRW Fits

We follow the standard practice in the literature to fit a DRW model to the quasar light curve (e.g., Kelly et al. 2009; Kozłowski et al. 2010; MacLeod et al. 2010; Suberlak et al. 2021; Burke et al. 2021). The details of the DRW modeling are provided in Appendix A2. The best-fit DRW parameters are compiled in the FITS catalog described in Table 1. An example DRW fit is shown in Fig. 5.

In Fig. 6, we show the distribution of our sample in the \(\tau_{\text{DRW}}\) versus \(SF_{\infty}\) plane, where \(\sigma_{\text{DRW}}\) is the long-term variability amplitude in the DRW model (see Appendix A2). With the SDSS-only baselines, we reproduce the results in MacLeod et al. (2010), with a median value for \(\tau_{\text{DRW,rest}}\) of ~ 540 days in the \(r\) band. Using SDSS+PS1-only baselines, however, we obtain a median value for \(\tau_{\text{DRW,rest}}\) of ~ 680 days in the \(r\) band, while Suberlak et al. (2021) quoted a value of ~ 550 days. We attribute this discrepancy to the method of choosing the best-fit value from the DRW fit (discussed further in Appendix A5). By extending the baseline further with the DES+DECam data, the values of \(\tau_{\text{DRW}}\) and \(SF_{\infty}\) continue to rise. The median values of \(\tau_{\text{DRW,rest}}\) and \(SF_{\infty}\) for S82 quasars with our final baselines are ~ 750 days and 0.25 mag in \(g\) band.

Fig. 7 compares the \(\tau_{\text{DRW,obs}}\) values measured with different baselines. Similar to the results shown in Fig. 6, the best-fit \(\tau_{\text{DRW,obs}}\) continues to increase as the baseline increases. With longer baselines and more epochs, the constraints on \(\tau_{\text{DRW}}\) are somewhat tighter, as demonstrated by the lower scatter of points with the SDSS+PS1 and SDSS+PS1+DES+DECam data than with the SDSS-only data in Fig. 7. However, the formal measurement uncertainties on \(\tau_{\text{DRW}}\) are only reduced by ~ 10% on average from the SDSS-only measurements to the SDSS+PS1+DES+DECam measurements. It is possible that the formal measurement uncertainties underestimated the true uncertainties on \(\tau_{\text{DRW}}\) in these studies.

Kozłowski (2017) emphasized the importance of the length of the light curve in constraining the DRW damping timescale. The best-fit \(\tau_{\text{DRW}}\) could be significantly underestimated if the light curve is not long enough, as independently confirmed in other studies with simulated light curves (e.g., Suberlak et al. 2021; Burke et al. 2021). The fact that the average \(\tau_{\text{DRW}}\) continues to rise as the baseline increases indicates that even the 20-year baseline is probably not long enough to well constrain \(\tau_{\text{DRW}}\) in some S82 quasars. On the other hand, the increasing \(\tau_{\text{DRW}}\) as the baseline increases may be due to gradual, long-term trends in the quasar light curve (see further discussion in Appendix A2), or it is possible that these quasar light curves are more complex than a simple DRW process with only one characteristic timescale.

Nevertheless, simulations with mock light curves have shown that the systematic bias in \(\tau_{\text{DRW}}\) is not significant, albeit with elevated scatter, when the measured \(\tau_{\text{DRW}}\) is less than 20% of the baseline (e.g., Kozłowski 2017; Suberlak et al. 2021; Burke et al. 2021). For example, around the 20% baseline mark, the bias in the median of the measured \(\tau_{\text{DRW}}\) is only ~ 0.12 – 0.15 dex from the simulations in the above studies, which is much smaller than the scatter of individual \(\tau_{\text{DRW}}\) measurements. Indeed, when we compare our best-fit DRW model to the ensemble SF and PSD measurements in §3.2 and §3.3, we find that these DRW fits and the associated damping timescales are qualitatively correct on average.

Next, we investigate the wavelength dependence of \(\tau_{\text{DRW}}\) using our measurements. To reduce the impact of poorly constrained \(\tau_{\text{DRW}}\) values from insufficient baselines, we only use a subset of 27 quasars with measured \(\tau_{\text{DRW}}\) less than 20% of the baseline, for which we consider the constraint on the damping timescale more reliable. Using a more stringent cut on the baseline criterion would be unnecessary, and would greatly reduce our sample statistics. Fig. 8 (left) displays the wavelength dependences of \(\tau_{\text{DRW}}\) and \(SF_{\infty}\). We find a weak wavelength dependence of \(\tau_{\text{DRW}} \propto \lambda^{0.17 \pm 0.07}\), which is slightly steeper than (but formally consistent within 2\(\sigma\)) the one reported in MacLeod et al. (2010) based on the much shorter SDSS-only light curves \(\tau_{\text{DRW}} \propto \lambda^{0.12 \pm 0.02}\). On the other hand, we recover a weak anti-correlation between \(SF_{\infty}\) and wavelength, but our dynamic range in wavelength is more limited than that in MacLeod et al. (2012), given that we only use data in \(gri\) bands. These constraints on wavelength dependences are weak given the small number of quasars that pass the baseline criterion. If we use the full sample of 190 quasars instead, we find slightly different, but fully consistent results (right panel of Fig. 8).

3.2 Structure Function Analysis

The structure function measures the magnitude difference for pairs of epochs separated at different timescales, and is a simple and useful empirical tool to characterize the variability of quasars (e.g., Collier & Peterson 2001; Kozłowski 2016b). Unlike the DRW model, the SF measurements are model-independent, and provide empirical constraints on variability amplitude as a function of timescales. However, unlike the DRW and higher order CARMA modelling, the SF approach does not rigorously deal with the flux uncertainties of each epoch, and unequal flux uncertainties for long-term pairs from different surveys may complicate the SF calculation. We therefore
This array is formatted as \([\text{lower error}, \text{value}, \text{upper error}]\). If the CARMA model fit to the light curve data is not a high enough order to have a certain light curves, so the “x” here corresponds to

The format of the FITS table compiling the properties for our sample of 190 quasars in S82.

| Column Name | Format | Unit | Description |
|-------------|--------|------|-------------|
| DBID        | int64  |      | Database ID for each quasar; same as in MacLeod et al. (2012) |
| RA          | float64 | deg  | Right ascension of the target |
| DEC         | float64 | deg  | Declination of the target |
| Z           | float64 |      | Redshift |
| log\_M\_BH  | float64 | \(\log_{10}(M_\odot)\) | log\_10 of the black hole mass |
| log\_M\_BH\_ERR | float64 | \(\log_{10}(M_\odot)\) | Error in \(\log_{10}\) of the black hole mass |
| log\_Lbol   | float64 | \(\log_{10}(\text{erg s}^{-1})\) | log\_10 of the bolometric luminosity |
| log\_Lbol\_ERR | float64 | \(\log_{10}(\text{erg s}^{-1})\) | Error in \(\log_{10}\) of the bolometric luminosity |
| log\_TAU\_OBS\_x | float64 | \(\log_{10}(\text{days})\) | \(\log_{10}(\tau_{\text{DRW}})\) in the observed-frame |
| log\_TAU\_OBS\_x\_ERR\_L | float64 | \(\log_{10}(\text{days})\) | Lower error of \(\log_{10}(\tau_{\text{DRW}})\) in the observed-frame |
| log\_TAU\_OBS\_x\_ERR\_U | float64 | \(\log_{10}(\text{days})\) | Upper error of \(\log_{10}(\tau_{\text{DRW}})\) in the observed-frame |
| log\_TAU\_REST\_x | float64 | \(\log_{10}(\text{days})\) | \(\log_{10}(\tau_{\text{DRW}})\) in the rest-frame |
| log\_TAU\_REST\_x\_ERR\_L | float64 | \(\log_{10}(\text{days})\) | Lower error of \(\log_{10}(\tau_{\text{DRW}})\) in the rest-frame |
| log\_TAU\_REST\_x\_ERR\_U | float64 | \(\log_{10}(\text{days})\) | Upper error of \(\log_{10}(\tau_{\text{DRW}})\) in the rest-frame |
| log\_SIGMA\_x | float64 | \(\log_{10}(\text{mag})\) | \(\log_{10}(\sigma_{\text{DRW}})\) |
| log\_SIGMA\_x\_ERR\_L | float64 | \(\log_{10}(\text{mag})\) | Lower error of \(\log_{10}(\sigma_{\text{DRW}})\) |
| log\_SIGMA\_x\_ERR\_U | float64 | \(\log_{10}(\text{mag})\) | Upper error of \(\log_{10}(\sigma_{\text{DRW}})\) |
| log\_JITTER\_x | float64 | \(\log_{10}(\text{mag})\) | \(\log_{10}(\sigma_{n})\) |
| log\_JITTER\_x\_ERR\_L | float64 | \(\log_{10}(\text{mag})\) | Lower error of \(\log_{10}(\sigma_{n})\) |
| log\_JITTER\_x\_ERR\_U | float64 | \(\log_{10}(\text{mag})\) | Upper error of \(\log_{10}(\sigma_{n})\) |
| SIG0\_x | float64 | mag | Intrinsic RMS variability |
| SIG0\_x\_ERR | float64 | mag | Error in intrinsic RMS variability |
| LAM\_W\_REST\_x | float64 | Å | Rest-frame wavelength the target was observed in |
| SURVEY\_x | str5 | | Imaging survey used for the observation |
| MJD\_x | float64 | days | MJD of the observation |
| MAG\_x | float64 | mag | PSF magnitude of the observation |
| MAG\_ERR\_x | float64 | mag | Error in the observation |
| OFFSET\_x | float64 | mag | Manual offset applied to the PS1 magnitudes |
| DT\_REST\_x | float64 | days | Rest-frame time lags used to construct the structure function |
| SF\_x | float64 | mag | Structure function measurements |
| SF\_x\_ERR\_L | float64 | mag | Lower error in the structure function |
| SF\_x\_ERR\_U | float64 | mag | Upper error in the structure function |
| CARMA\_P\_x | int64 | | CARMA model p parameter |
| CARMA\_Q\_x | int64 | | CARMA model q parameter |
| REST\_FREQ\_x | float64 | days\(^{-1}\) | Rest-frame frequency |
| CARMA\_PSD\_x | float64 | (mag)\(^{2}\) (days) | Median PSD constructed from the CARMA model |
| CARMA\_PSD\_x\_ERR\_L | float64 | (mag)\(^{2}\) (days) | Lower error in the CARMA PSD |
| CARMA\_PSD\_x\_ERR\_U | float64 | (mag)\(^{2}\) (days) | Upper error in the CARMA PSD |
| CARMA\_AR0\_x | float64 | | 0\(^{th}\) CARMA auto-regressive parameter (\(a_{0}\)) |
| CARMA\_AR1\_x | float64 | | 1\(^{st}\) CARMA auto-regressive parameter (\(a_{1}\)) |
| CARMA\_AR2\_x | float64 | | 2\(^{nd}\) CARMA auto-regressive parameter (\(a_{2}\)) |
| CARMA\_AR3\_x | float64 | | 3\(^{rd}\) CARMA auto-regressive parameter (\(a_{3}\)) |
| CARMA\_AR4\_x | float64 | | 4\(^{th}\) CARMA auto-regressive parameter (\(a_{4}\)) |
| CARMA\_AR5\_x | float64 | | 5\(^{th}\) CARMA auto-regressive parameter (\(a_{5}\)) |
| CARMA\_AR6\_x | float64 | | 6\(^{th}\) CARMA auto-regressive parameter (\(a_{6}\)) |
| CARMA\_AR7\_x | float64 | | 7\(^{th}\) CARMA auto-regressive parameter (\(a_{7}\)) |
| CARMA\_MA0\_x | float64 | | 0\(^{th}\) CARMA moving-average parameter (\(\beta_{0}\)) |
| CARMA\_MA1\_x | float64 | | 1\(^{st}\) CARMA moving-average parameter (\(\beta_{1}\)) |
| CARMA\_MA2\_x | float64 | | 2\(^{nd}\) CARMA moving-average parameter (\(\beta_{2}\)) |
| CARMA\_MA3\_x | float64 | | 3\(^{rd}\) CARMA moving-average parameter (\(\beta_{3}\)) |
| CARMA\_MA4\_x | float64 | | 4\(^{th}\) CARMA moving-average parameter (\(\beta_{4}\)) |
| CARMA\_MA5\_x | float64 | | 5\(^{th}\) CARMA moving-average parameter (\(\beta_{5}\)) |
| CARMA\_MA6\_x | float64 | | 6\(^{th}\) CARMA moving-average parameter (\(\beta_{6}\)) |

\(^{a}\) Each column labeled with “x” is three columns, with “x” representing the value obtained from data in the \(g, r,\) or \(i\) bands.

\(^{b}\) FITS tables require that each entry in a column of data have the same length. However, each object has a different amount of epochs, making their data arrays unequal. To circumvent this, we have made the arrays corresponding to properties of the observations of the object (SURVEY, MJD, MAG, MAG\_ERR) the same length. This length is the number of observations for the object with the maximum number of observations in the sample. For arrays with a length less than this maximum length, we fill the arrays with NaNs or empty strings until they reach this length.

\(^{c}\) This manual offset is used to bring the PS1 and DES magnitudes into agreement in the overlapping region. Offsets were only applied to \(r\)-band and \(i\)-band light curves, so the “x” here corresponds to \(r\) and \(i\) only.

\(^{d}\) All of the entries for the CARMA parameters are given as 3-entry arrays, consisting of the 1\(\sigma\) errors (absolute values) and median value of the parameter. This array is formatted as \([\text{lower error, value, upper error}]\). If the CARMA model fit to the light curve data is not a high enough order to have a certain parameter, it will have an array filled with zeros. For example, if the CARMA p parameter is 3, all CARMA auto-regressive parameters greater than 3 will be \([0, 0, 0]\) in the FITS table.
Figure 5. An example of fitting the $g$-band light curve with the DRW model using the fast Gaussian process solver Celerite (discussed further in A2). The top panel displays the raw light curve of the object, and the predicted light curve from the DRW model using the best-fit, maximum likelihood parameters. The orange line represents the median value of the prediction, while the shaded orange region represents the area between the 1σ uncertainty in the prediction. The plot on the lower-left displays the probability distributions of the DRW parameters fit for by Celerite, with $\sigma_{\text{DRW}}$ representing the standard deviation of long-term variability, $\tau_{\text{DRW}}$ here representing the observed-frame characteristic timescale, and $\sigma_{\text{n}}$ representing a noise term (also called jitter). The shaded regions in the probability distributions correspond to where $\tau_{\text{DRW,obs}}$ is greater than 20% of the baseline. The lower right plot shows the observed-frame PSD of the light curve from both the raw data and drawing from the posterior distribution of the Celerite fit. The model PSD is shown in orange (with a band spanning the 1σ uncertainties), the Lomb-Scargle periodogram (Lomb 1976; Scargle 1982) is shown in blue, and the binned Lomb-Scargle periodogram is shown in black. The binned Lomb-Scargle periodogram was also fit to a broken power law (shown as a red line), whose break frequency (and corresponding 1σ errors) are shown with the red arrow and bar. The regions shaded red in the PSD plot correspond to regions of frequency space not sampled by the light curve (i.e. larger than the minimum cadence) as well as regions with timescales longer than 20% of the baseline (i.e. $t < t_{\text{baseline}}/5$). The difference between the Lomb-Scargle periodogram and the model PSD is caused by the difficulties of measuring the PSD accurately using the Fourier method and irregularly sampled light curves, contributions from flux uncertainties in the periodogram measurement, as well as potential deviations from a DRW model.

We measure the SF for individual quasars in our sample as well as for the ensemble average. We have followed Kozłowski (2016b) to calculate the SF after subtracting photometric uncertainties (e.g., from flux uncertainties and additional systematics from host galaxy light and seeing variations) using close pairs separated by less than ~ 10 days in rest-frame. Fig. 9 and Fig. 10 display the ensemble SF for different subsamples, where the full sample is divided into subsamples with approximately the same number of objects in each division (either by $\tau_{\text{DRW}}$ or by $L_{\text{bol}}/z$).

Fig. 9 compares the ensemble SF with the median DRW model for subsets of quasars binned by the measured $\tau_{\text{DRW}}$. The SF does show a flattening roughly around the location of $\tau_{\text{DRW}}$ measured from the
3.3 Power Spectrum Density Analysis

We measure the optical variability PSD using our sample and light curve data set. Because our light curves are irregularly sampled with large seasonal gaps, it is challenging to directly measure the PSD using the Fourier method, which suffers from aliasing and power leakage from windowing effects. Instead, we take advantage of the recent development of fitting Gaussian random process models to time series data and recovering the PSD (Kelly et al. 2014). Such an alternative approach is more robust in measuring the PSD with sparsely and irregularly sampled light curve data (e.g., Kelly et al. 2014; Simm et al. 2016), and properly deals with uneven measurement uncertainties in the light curve.

Specifically, we use the CARMA_pack developed by Kelly et al. (2014) to find the best-fit CARMA(p,q) model to the light curve and derive the PSD, where (p,q) are the numbers of auto-regression (AR) and moving average (MA) terms, respectively. The technical details of CARMA fits are described in Appendix A3. We show an example of PSD analysis in Fig. 11, and all the individual and ensemble PSDs are provided in the FITS catalogs described in Tables 1 and 2.

We show the distributions of the best-fit values of p and q in Fig. 12. There is a tendency of clustering near p ≈ 4 and q ≈ 1 – 2, which may indicate the general similarity of quasar variability PSDs. However, we found that a forced CARMA(2,1) model fit produces very similar PSDs to the ones from the best-fit higher-order CARMA models. Indeed, the preference based on the model selection criterion described in Appendix A3 is not obvious among the higher-order CARMA models; but the preference of a higher-order CARMA model over the DRW model is often significant (e.g., Kelly et al. 2014). In particular, the CARMA(2,1) model is also known as the damped harmonic oscillator (DHO) model, which is argued to be a superior statistical description for quasar variability than the simpler DRW model (e.g., Kasliwal et al. 2017; Moreno et al. 2019; Yu et al. 2022).

Fig. 13 displays all CARMA PSDs for our sample in the rest-frame of the quasar (only showing the best-fit model), color-coded by different properties. While these individual PSDs overlap considerably

Table 2. The format of the FITS table compiling ensemble SF and PSD measurements from subsets of our full quasar sample.

| Column Name                | Format       | Unit     | Description                                                                 |
|----------------------------|--------------|----------|-----------------------------------------------------------------------------|
| Subsample                  | str9         |          | Description of the ensemble                                                 |
| DBIDs_x                    | float64      |          | Database IDs of the objects included in the ensemble                        |
| DT_REST_x                  | float64      | days     | Rest-frame time lags used to construct the structure function               |
| SF_x                       | float64      | mag      | Ensemble structure function measurements                                    |
| SF_x_ERR                   | float64      | mag      | Error in structure function measurements                                    |
| REST_FREQ_x                | float64      | days⁻¹   | Rest-frame frequency                                                        |
| CARMA_PSD_x                | float64      | (mag)²   | Ensemble of the median PSDs of the optimal CARMA models for each object     |
| CARMA_PSD_x_ERR_L          | float64      | (mag)²   | Lower error in the ensemble PSD                                            |
| CARMA_PSD_x_ERR_U          | float64      | (mag)²   | Upper error in the ensemble PSD                                            |

Similar to Table 1, all columns with names containing an “x” are three separate columns, where x is replaced with gri, corresponding to values in each of the three bands.

There are four different types of ensembles described in this table in general: the total sample, the samples split by τ_{DRW,rest}, and the samples split in a grid by bolometric luminosity and redshift. The total subsample is labeled “Total”, the three samples split by τ_{DRW,rest} are labeled “Tau{i}” (where i = 1, 2, 3), and the five samples split by luminosity and redshift are labeled “Lz_grid{ij}” (where i, j = 1, 2, 3 represents their placement on the grid).

Figure 6. Contour plots showing the distribution of $SF_\infty$ and $\tau_{DRW}$ fitted from our quasar light curve sample. There are three contours for each band, representing data fitted from light curves using only SDSS, SDSS and PS1, and all of the data. The contours for each dataset enclose $[33, 66, 100]\%$ of the distribution respectively.

DRW fits, indicating the presence of such a damping timescale on the order of hundreds of days.

We also recover the well known dependences of variability amplitude on wavelength and luminosity of quasars using ensemble SF measurements (data required to generate these plots are provided in Table 2).
Figure 7. Comparisons between $\tau_{DRW, obs}$ measurements from DRW fits with different baselines. The upper panels compare the $\tau_{DRW, obs}$ fitted from only using SDSS data (a ~10 yr baseline) to the $\tau_{DRW, obs}$ fitted from the entire 20 yr dataset for the three bands. The lower panels compare the $\tau_{DRW, obs}$ fitted using data from SDSS and PS1 (a ~15 yr baseline) to those fitted using the full light curves. The red shaded area indicates where $\tau_{DRW, obs}$ is greater than the light curve baseline, on each respective axis. The red line running through the data shows the unity relation.

Figure 8. Wavelength dependences of both $\tau_{DRW}$ and $\tau_{SF}$. The left panels are for a subset of 27 quasars for which all measured $\tau_{DRW, obs}$ values are less than 20% of the final baseline. The right panels are for the full sample of 190 quasars. The contours in blue, red, and orange represent the results from $g$, $r$, and $i$ light curves, respectively, shifted to the corresponding rest-frame wavelengths of each individual quasar. The contours for each band represent 30 and 70 percent of the data. The best-fit linear regression model and 1\$σ$ uncertainties using the method described in Kelly (2007) are shown in the black line and shaded area, with the best-fit slopes marked in each panel.

given their measurement uncertainties, there are trends of the PSD amplitude and shape with luminosity and black hole mass of the quasar. In addition, the CARMA PSD tends to flatten out sooner at the low-frequency end for light curves with shorter $\tau_{DRW}$, suggesting that the DRW fits are reasonable in constraining the long-term damping timescale.

Fig. 14 shows the ensemble CARMA PSD for the full sample in the three bands. The ensemble PSDs are tightly constrained over days to decade timescales, and show a clear wavelength dependence. Fig. 15 and Fig. 16 display the ensemble PSDs for the same subsets of quasars used in our SF analysis. When divided by the best-fit $\tau_{DRW}$, the ensemble PSD agrees with the average DRW model in the subsample reasonably well, suggesting the DRW model provides a reasonable description of the underlying PSD. However, the more flexible CARMA model reveals a sharper decline in the variability power below timescales of a few weeks than the $f^{-2}$ power-law, consistent with earlier findings with other light curve samples (e.g., Mushotzky et al. 2011; Zu et al. 2013). In Appendix A5, we demon-
measurements suggests that the long-term characteristic variability damping timescale from a few months to a few years. The qualitative agreement between the DRW model and SF/PSD description, describes the stochastic optical quasar light curves reasonably well over rest-frame timescales from a few months to a few years. The qualitative agreement between the DRW model and SF/PSD measurements suggests that the long-term characteristic variability timescale captured by the DRW model is reliable on average. Indeed, Burke et al. (2021) tested DRW fits to non-DRW light curves with a characteristic long-term turnover timescale in the PSD and found that the best-fit $\tau_{\text{DRW}}$ correctly recovers this timescale.

Figure 9. Ensemble structure functions for different ensembles of the 190 quasars in our sample, grouped by their fitted $\tau_{\text{DRW,rest}}$. The objects are grouped such that there are an equal number of quasars in each ensemble, resulting in uneven bin widths in $\tau_{\text{DRW,rest}}$. The ensemble structure function for the full sample is overlaid in red, while the structure functions for the individual subsamples are plotted in black. The predicted structure functions using the fitted SF$_{\text{ro}}$ and $\tau_{\text{DRW}}$ are plotted in gray. To obtain this DRW prediction, we sample 500 predicted DRW structure functions from each target in the ensemble, drawn from a Gaussian distribution using its best-fit DRW parameters and their uncertainties. We then combine the samples for all targets and use the median value in each $\Delta t$ bin (shown as the gray line) as the DRW-predicted structure function, and the 16th and 84th in each $\Delta t$ bin (colored in a gray band around the median) to construct the errors in the DRW prediction.

4 DISCUSSION

4.1 The wavelength dependence of $\tau_{\text{DRW}}$

We find that the DRW damping timescale only weakly depends on wavelength, consistent with earlier studies with shorter light curves. This weak wavelength dependence of the damping timescale is difficult to interpret: if $\tau_{\text{DRW}}$ tracks the local timescale of the accretion disk, e.g., the thermal timescale, then we expect a stronger wavelength dependence of this timescale because the local thermal timescale scales with the emitting wavelength as $\tau \propto \lambda^2$ in the standard $\alpha$-disk model (Shakura & Sunyaev 1973). One possibility, as suggested by Burke et al. (2021), is that the observed UV/optical variability is driven by processes in the inner (UV-emitting) part of the accretion disk, which rapidly propagates outwards at the Alfvén speed, during which the characteristic variability timescale is more or less preserved. Alternatively, the observed damping timescale may be the thermal timescale averaged over different radii, leading to a shallower wavelength dependence (e.g., Sun et al. 2020). Further development of these theoretical ideas, combined with dedicated global radiation MHD simulations (e.g., Jiang et al. 2019) will shed light on the nature of this long-term characteristic variability damping timescale.

4.2 Validity of the DRW prescription

Overall, we find that the DRW model, even though an empirical prescription, describes the stochastic optical quasar light curves reasonably well over rest-frame timescales from a few months to a few years. The qualitative agreement between the DRW model and SF/PSD measurements suggests that the long-term characteristic variability...

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Overall, we find that the DRW model, even though an empirical prescription, describes the stochastic optical quasar light curves reasonably well over rest-frame timescales from a few months to a few years. The qualitative agreement between the DRW model and SF/PSD measurements suggests that the long-term characteristic variability...
Figure 10. Ensemble $g$-band structure functions for different subsets of the full sample, grouped by their bolometric luminosity and redshift. Similar to Fig. 9, we group these objects such that there is nearly an equal amount of objects in each bin. The quasars with the highest luminosities are spread over a large redshift range, which is split into three redshift bins to retain an equal number of quasars in each bin. This process was followed for the second and third luminosity bins, leaving only one redshift bin for the lowest luminosity bin. As a result, the redshift ranges are different for different luminosity bins. Each subsample contains ~30 objects. The redshift ranges are listed above each subsample, and the $L_{\text{bol}}$ ranges are shown on the leftmost axis, being $[45.09, 45.71]$, $[45.71, 46.18]$ and, $[46.18, 47.04]$. Each subsample in a given row has the same range of $L_{\text{bol}}$. We have subtracted an “SF floor” seen in time lags below ~10 days, to remove contamination from PSF variations and host-galaxy flux (discussed further in Appendix A1). The ensemble SF for the full sample and the DRW-prediction for each subsample are also shown for reference. We constructed the ensemble DRW-predicted structure functions in the same manner as those presented in Fig. 9.

are largely determined by the data. There is evidence (e.g., Fig. 15) that this short timescale cutoff of power is positively correlated with the long-term damping timescale. To further illustrate this point, we fit a doubly-broken power-law model to the three ensemble PSDs divided by the measured $\tau_{\text{DRW, rest}}$ in Fig. 15: $P \propto 1/[1 + (f/f_0)^2 + (f/f_1)^4]$. This PSD model fits the three ensemble PSDs reasonably well over years to days timescales, as shown in Fig. 17. The two break timescales, $\tau_0 = 1/(2\pi f_0)$ and $\tau_1 = 1/(2\pi f_1)$, indeed vary in concordance in the three ensembles.

While our sample is small and the dynamic range in black hole mass or quasar luminosity is limited, there is also some tentative evidence that this high-frequency-end break occurs at shorter timescales for lower-luminosity (and less massive) quasars (Fig. 16). This point is further illustrated in Fig. 18, where we compare the ensemble PSDs for subsamples divided by black hole mass. If we assume both break timescales scale with black hole mass as $M_{\text{BH}}^{0.5}$ (Burke et al. 2021), we expect much shorter high-frequency break timescales in low-redshift Seyferts ($M_{\text{BH}} \sim 10^7 M_\odot$) than in SDSS quasars ($M_{\text{BH}} \sim 10^9 M_\odot$). This may explain the much shorter (a few days) cutoff timescales found for low-redshift, low-luminosity AGNs that are two orders of
Figure 11. An example of CARMA model-fit PSDs for our quasar sample. The CARMA-predicted PSD (discussed further in A3) is shown in blue, where the median from the posterior is the solid line and the shaded region encloses the 1σ uncertainty range. The median noise level derived from the raw light curve data (2 × median(Δf) × median(σ f 2)) is shown as the red horizontal line. The gray dashed line indicates a $\propto f^{-2}$ PSD. A DRW-fit PSD for the same example light curve is shown as a black line for comparison, with the 1σ uncertainty range shaded in gray. The CARMA-predicted PSDs for individual targets are compiled in the FITS catalog described in Table 1.

magnitude less massive than SDSS quasars (e.g., Mushotzky et al. 2011).

The physical origin of the suppression of variability power on timescales shorter than ~ 1 month is unclear. It could be due to the intrinsic shape of the variability PSD, e.g., resulting from the break in the driving variability PSD and/or damping processes in the accretion disk (e.g., Sun et al. 2020). An alternative explanation, as pointed out by, e.g., Tachibana et al. (2020), is due to an averaging effect. Even if the flux of the accretion disk varies coherently, emission from different parts of the disk or from more spatially-extended regions (e.g., an extended diffuse continuum emission region or the broad-line region) will arrive at different times. The observed variable flux is then the convolution of the intrinsic variability pattern with the transfer function describing the time delays from different locations. Tachibana et al. (2020) showed that, with a likely transfer function form (a semi-circle with a characteristic timescale of a month), the short-time variability power will be reduced due to averaging, producing a PSD slope close to −4 beyond this characteristic frequency. In general, such transfer functions would reduce the high-frequency power, leading to a steeper high-frequency end slope in the observed PSD. In both the intrinsic PSD scenario and the “smearing” scenario, it is possible that the characteristic timescale of this second high-frequency-end break, which reflects some characteristic size of the emission region, depends on the physical properties of the quasar, such as the black hole mass (Sun et al. 2020; Tachibana et al. 2020), in a similar way as the long-term damping timescale $\tau_{DRW}$.

5 CONCLUSIONS

Given the simplicity of the DRW model and its reasonable success to fit quasar light curves, it has become increasingly popular to use the DRW prescription to describe stochastic quasar variability. However, the validity of the DRW prescription has to be tested with high-quality light curve data that are well sampled, have sufficient baselines and adequate S/N. Some recent light curve samples already have sufficient quality to reveal evidence for deviations from the DRW prescription either for individual objects or for large quasar samples (e.g., Mushotzky et al. 2011; Zu et al. 2013; Kashiwai et al. 2015; Caplar et al. 2017; Yu et al. 2022).

In this work we have measured the optical continuum variability of a sample of 190 quasars from the SDSS Stripe 82 region. Our quasar sample has been photometrically monitored in the SDSS, PS1, DES surveys, as well as our continued monitoring with DECam. The light curves of our sample span a baseline of ~ 20 years with ~ 200 epochs in each of the gri bands. We fit these light curves with the DRW model, and measured the structure function and power spectrum density using the CARMA models. The main findings from our work are the following:

- The best-fit DRW parameters ($\tau_{DRW}$ and $\sigma_{\text{in}}$) continue to rise with our light curve data, compared with earlier studies with shorter (e.g., 10-yr and 15-yr) baselines from SDSS-only (MacLeod et al. 2010) and SDSS+PS1 (Suberkol et al. 2021). The average rest-frame $\tau_{DRW}$ ~ 750 days in g band for S82 quasars with our 20-yr light curves.
- While the $\tau_{DRW}$ measurements for many S82 quasars are still not well constrained with the 20-yr light curves, we believe that the bias from insufficient baselines is reduced compared with earlier studies based on shorter baselines, if the underlying variability process is indeed a single DRW. However, we caution that realistic quasar light curves may be more complicated than a single DRW process, e.g., multiple variability processes with different characteristic timescales and/or non-stationary variability processes could be at work. In such cases, the results from a single DRW fit will depend on the baseline. More extended light curves are required to test this possibility.
- Using a subset of 27 quasars for which we have relatively better-constrained $\tau_{DRW}$ in the g, r and i bands, we confirm a weak wavelength dependence of $\tau_{DRW} \propto \lambda^{0.51 \pm 0.20}$ ($\tau_{DRW} \propto \lambda^{0.54 \pm 0.10}$ for the full sample). This wavelength dependence is slightly stronger than previous results $\tau_{DRW} \propto \lambda^{0.17}$ based on 10-yr light curves (MacLeod et al. 2010), although these results are formally consistent within 2σ.
- We also measured the optical SF and PSD of our quasar sample. The baseline and sampling of our light curves enabled reliable constraints of the ensemble PSD over days to decades timescales. Comparisons between the ensemble SF and PSD with predictions from the best-fit DRW models suggest that the DRW prescription provides a reasonably good description of the variability properties of quasars over months to years timescales. But the average PSD slope on timescales shorter than ~ a month is noticeably steeper than the DRW model, consistent with earlier findings (e.g., Mushotzky et al. 2011; Zu et al. 2013). There is tentative evidence that this high-frequency cutoff timescale correlates with the low-frequency damping timescale $\tau_{DRW}$, hence both timescales may have similar dependences on physical properties of the quasar (e.g., Burke et al. 2021).

We continue to monitor our quasar sample during 2020-2024 as part of our ongoing effort to photometrically monitor deep extragalactic fields with ample multi-wavelength and time-domain data. With another ~ 5 year extension of the baseline and seamlessly merg-
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This research made use of matplotlib, a Python library for publication quality graphics (Hunter 2007). This research made use of SciPy (Virtanen et al. 2020). This research made use of Astropy, a community-developed core Python package for Astronomy (Astropy Collaboration et al. 2018). This research made use of NumPy (Harris et al. 2020). This research made use of pandas (McKinney 2011).

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Figure 13 shows the rest-frame CARMA model PSDs in our parent sample, color-coded by different attributes of the target: $\log_{10}(f_{\text{DRW,rest}})$, $\log_{10}(L_{\text{bol}})$, and $\log_{10}(M_{\text{BH}})$. Each panel shows the black horizontal line representing the median noise level of the individual light curves, and the dashed gray line represents a $\propto f^{-2}$ PSD. There are some general trends visible, e.g., lower PSD amplitudes for higher-luminosity quasars, and faster flattening of the PSD at the low-frequency end for quasars with shorter damping timescales in the DRW fits.

Figure 14 illustrates the rest-frame ensemble PSDs for the full sample in $gri$ bands. Each quasar light curve was fit using CARMA_pack, a code designed to fit time-series data to CARMA models using the method described in Kelly et al. (2014), with optimized $(p,q)$ parameters for the CARMA model. The black line shows the median value from the ensemble, and the light shaded area indicates the nominal uncertainty of the ensemble PSD.
Figure 15. Ensemble CARMA PSDs for subsamples divided by their best-fit \(r_{\text{DRW}}\) from §3.1. The first three panels show these ensemble PSDs corresponding to each subsample, whose \(r_{\text{DRW}}\) ranges are shown above each panel. The DRW-predicted ensemble PSDs are shown in the purple-shaded area for each ensemble. The ensemble DRW-predicted PSDs are constructed in the same manner as the ensemble DRW-predicted structure functions, shown in Fig. 9. The rightmost panel shows the PSDs of all three ensembles superimposed on the ensemble PSD for the full sample (shown in black). The two gray dashed lines in each panel correspond to \(f^{-2}\) and \(f^{-4}\) power laws.

DATA AVAILABILITY

We provide all light curve data and time series measurements in two online FITS tables located at https://zenodo.org/record/5842449#.YipOg-jMJPY. The format of these FITS tables is described in Tables 1 and 2.

REFERENCES

Ai Y. L., Yuan W., Zhou H. Y., Wang T. G., Dong X.-B., Wang J. G., Lu H. L., 2010, ApJ, 716, L31
Akaike H., 1973, Proceedings of the Second International Symposium on Information Theory ed. B. Petrov & F. Csaki (Budapest: Akademiai Kiado), p. 267–281
Astropy Collaboration et al., 2018, AJ, 156, 123
Bauer A., Baltay C., Coppi P., Eillman N., Jerke J., Rabinowitz D., Scalzo R., 2009, ApJ, 696, 1241
Burke C. J., et al., 2021, Science, 373, 789
Caplar N., Lilly S. J., Trakhtenbrot B., 2017, ApJ, 834, 111
Caplar N., Pena T., Johnson S. D., Greene J. E., 2020, ApJ, 889, L29
Chambers K. C., et al., 2016, arXiv e-prints,
Chen X.-Y., Wang J.-X., 2015, ApJ, 805, 80
Collier S., Peterson B. M., 2001, ApJ, 555, 775
De Cicco D., et al., 2019, A&A, 627, A33
Drlica-Wagner A., et al., 2018, ApJS, 235, 33

Foreman-Mackey D., Hogg D. W., Lang D., Goodman J., 2013, PASP, 125, 306
Foreman-Mackey D., Agol E., Ambikasaran S., Angus R., 2017, AJ, 154, 220
Giveon U., Maoz D., Kaspi S., Netzer H., Smith P. S., 1999, MNRAS, 306, 637
Guo H., Wang J., Cai Z., Sun M., 2017, ApJ, 847, 132
Harris C. R., et al., 2020, Nature, 585, 357
Hartley W. G., et al., 2022, MNRAS, 509, 3547
Hawkins M. R. S., 2002, MNRAS, 329, 76
Hu Z., Tak H., 2020, AJ, 160, 265
Hunter J. D., 2007, Computing In Science & Engineering, 9, 90
Harvich C. M., Tsai C.-L., 1989, Biometrika, 76, 297
Ivezić Ž., et al., 2019, ApJ, 873, 111
Jiang Y.-F., Blaes O., Stone J. M., Davis S. W., 2019, ApJ, 885, 144
Kasliwal V. P., Vogeley M. S., Richards G. T., 2015, MNRAS, 451, 4328
Kasliwal V. P., Vogeley M. S., Richards G. T., 2017, MNRAS, 470, 3027
Kelly B. C., 2007, ApJ, 665, 1489
Kelly B. C., Bechtold J., Siemiginowska A., 2009, ApJ, 698, 895
Kelly B. C., Becker A. C., Sobolewska M., Siemiginowska A., Utley P., 2014, ApJ, 788, 33
Kozłowski S., 2016a, MNRAS, 459, 2787
Kozłowski S., 2016b, ApJ, 826, 118
Kozłowski S., et al., 2010, ApJ, 708, 927
Laurenti M., Vagnetti F., Middel R., Paolillo M., 2020, MNRAS, 499, 6053
Li Z., McGreer I. D., Wu X.-B., Fan X., Yang Q., 2018, ApJ, 861, 6
Liu T., et al., 2016, ApJ, 833, 6
Lomb N. R., 1976, Ap&SS, 39, 447
Luo Y., Shen Y., Yang Q., 2020, MNRAS, 494, 3868
MacLeod C. L., et al., 2010, ApJ, 721, 1014
MacLeod C. L., et al., 2012, ApJ, 753, 106
McKinney W., 2011, Python for High Performance and Scientific Computing, 14
Moreno J., Vogeley M. S., Richards G. T., Yu W., 2019, PASP, 131, 063001
Morganson E., et al., 2014, ApJ, 784, 92
Morganson E., et al., 2018, PASP, 130, 074501
Mushotzky R. F., Edelson R., Baumgartner W., Gandhi P., 2011, ApJ, 743, L12
Padovani P., et al., 2017, A&ARv, 25, 2
Rumbaugh N., et al., 2018, ApJ, 854, 160
Sánchez-Sáez P., Lira P., Mejía-Restrepo J., Ho L. C., Arévalo P., Kim M., Cartier R., Coppi P., 2018, ApJ, 864, 87

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Figure 16. Similar to Fig. 9, we group the full sample by $L_{\text{bol}}$ and redshift and create ensemble PSDs. For each panel, the ensemble PSD is shown in blue, the ensemble PSD for the whole sample is shown in black, and the two gray dashed lines indicate a $f^{-2}$ PSD and a $f^{-4}$ PSD. The range of redshifts of each subsample is labeled above each panel, and the range of bolometric luminosities is indicated on the axis on the left. Subsamples in the same row have the same luminosity range (this is not true for the same column with slightly different redshift ranges). The artificial turnover of power at the lowest frequencies is caused by the limited number of objects (~10) with the proper temporal coverage.

Scargle J. D., 1982, ApJ, 263, 835
Scaringi S., et al., 2015, Science Advances, 1, e1500686
Sesar B., et al., 2006, AJ, 131, 2801
Shakura N. I., Sunyaev R. A., 1973, A&A, 24, 337
Shen Y., et al., 2011, ApJS, 194, 45
Shen Y., et al., 2019, ApJS, 241, 34
Simm T., Salvato M., Saglia R., Ponti G., Lanzuisi G., Trakhtenbrot B., Nandra K., Bender R., 2016, A&A, 585, A129
Smith K. L., Mushotzky R. F., Boyd P. T., Malkan M., Howell S. B., Gelino D. M., 2018, ApJ, 857, 141
Suberlak K. L., Ivezić Z., MacLeod C., 2021, ApJ, 907, 96
Sun Y.-H., Wang J.-X., Chen X.-Y., Zheng Z.-Y., 2014, ApJ, 792, 54
Sun M., et al., 2020, ApJ, 891, 178
Tachibana Y., Graham M. J., Kawai N., Djorgovski S. G., Drake A. J., Mahabal A. A., Stern D., 2020, ApJ, 903, 54
Ulrich M.-H., Maraschi L., Urry C. M., 1997, ARA&A, 35, 445
Vanden Berk D. E., et al., 2004, ApJ, 601, 692
Virtanen P., et al., 2020, Nature Methods, 17, 261
Xin C., Charisi M., Haiman Z., Schiminovich D., 2020, MNRAS, 495, 1403
Yu W., Richards G. T., 2022, EzTao: Easier CARMA Modeling (ascl:2201.001)
Yu W., Richards G. T., Vogeley M. S., Moreno J., Graham M. J., 2022, arXiv e-prints, p. arXiv:2201.08943
Zu Y., Kochanek C. S., Kozlowski S., Udalski A., 2013, ApJ, 765, 106
de Vries W. H., Becker R. H., White R. L., Loomis C., 2005, AJ, 129, 615
However, without accounting for the flux measurement uncertainties, structure function measurements at small $\Delta t$ will level off to a certain “SF floor”. Therefore, using the method described by Kozłowski (2017), we subtract the measurement errors of both observations in the pair in quadrature:

$$SF(\Delta t) = \sqrt{\frac{1}{N_{\Delta t}} \sum_{i<j} ((y_i - y_j)^2 - \sigma_i^2 - \sigma_j^2)} ,$$

(A1)

where $\sigma_i$ and $\sigma_j$ are the measurement errors in observations $y_i$ and $y_j$ respectively.

The structure function is related to the auto-correlation function (ACF) of the light curve. Assuming that the variability of the source is stationary, we can use the covariance of two signals to compute the structure function:

$$SF(\Delta t) = \sqrt{2\sigma^2_s(1 - ACF(\Delta t))} ,$$

(A2)

where $\sigma_s$ is the variability amplitude intrinsic to the source. Taking the limit as $\Delta t \to \infty$, we obtain:

$$SF(\Delta t) = SF_{\infty} \sqrt{1 - ACF(\Delta t)} ,$$

(A3)

where $SF_{\infty}^2 = 2\sigma^2_s$ is the value of the structure function as $\Delta t \to \infty$. Assuming the variability is stationary (meaning the mean value of the light curve does not change), the difference between signals at large time lags will approach a constant value proportional to the intrinsic variability amplitude (white noise). The structure function will also flatten to white noise at very short time lags, where the change in magnitude is on the order of the measurement uncertainty.

We utilize Eqn. A1 to make all of our structure function measurements, where time lags are shifted to the rest-frame of the quasar. We also make ensemble structure function measurements for various subsamples of our 190 quasar dataset. To derive ensemble structure functions from individual objects, we bin the structure functions of each individual object into the same $\Delta t$ grid. We then take the median of each bin to be the ensemble measurement for that time lag, and use the uncertainty on the median (the standard deviation of the samples in each bin, divided by $\sqrt{N}$ the number of samples in the bin) to represent the uncertainty in that measurement. We create these ensemble structure functions for the total sample, three subsamples...
grouped by their fitted $\tau_{\text{DRW}}$, and six subsamples grouped by their bolometric luminosity and redshift.

For g-band measurements, through visual inspection, we observed that the structure function began to rise near time lags of 10 days. However, when measuring these ensemble structure functions, we noticed that they started to flatten at time lags less than days to weeks in the quasar rest frame). This proved to be more prevalent for structure functions in the r and i bands, where the structure function would be almost constant until $\Delta t_{\text{rest}} \sim 5$-10 days and then jump. We attribute this flattening to PSF seeing variations on short timescales, measurement uncertainties, as well as host galaxy contamination. To minimize the effect of this flattening, we perform linear regression (in log-space) on this floor using the method of Kelly (2007) and subtract the best-fit line from the full ensemble structure function. This floor stopped at different time lags for each band, [5,20,40] days for gr i measurements respectively, which we use to set the linear regression range.

For each ensemble structure function, excluding for the total sample, we also overlay the DRW model prediction for comparison. The DRW-predicted structure functions are also ensembles, using the predicted $\tau_{\text{DRW}}$ and $\sigma_{\text{DRW}}$ and Eqn. A6. These ensemble DRW-predicted structure functions are obtained in a similar manner to the ensemble structure functions themselves: we create structure functions for each target in the ensemble using the best-fit DRW parameters, then we bin the structure functions onto a common domain. Quasar variability studies in the frequency domain are sub-

### A2 The Damped Random Walk Model

The Damped Random Walk model, also known as the Ornstein-Uhlenbeck process, is a statistical model used to describe the stochastic variability from the accretion disk emission of quasars. This Gaussian process is the simplest model of a family of Gaussian processes known as continuous auto-regressive moving-average (CARMA) models. General CARMA models, discussed in §A3, specify that the output of the model is linear in the current and past terms in the time-series. This is seen in the DRW model (a CARMA(1,0) model), as it has a term that pushes large deviations from the mean of the time-series back towards the mean. It is useful to model light curves with the DRW model as it has parameters that can potentially connect to physical parameters of the quasar, and it can be modelled directly in the time domain instead of the frequency domain. Quasar variability studies in the frequency domain are subject to windowing effects, as large gaps in the data can lead to power leakage and aliases. Using a DRW model (or any CARMA model) can mediate these adverse effects.

All Gaussian processes require a covariance matrix (also known as a kernel), governing the relationship between two points in a time series. In the case of a DRW process, the covariance matrix is

$$k(t_{nm}) = \sigma^2_{\text{DRW}} \exp(-\tau_{nm}/\tau_{\text{DRW}}), \quad \text{(A4)}$$

where $t_{nm} = |t_n - t_m|$ and $t_n, t_m$ are times within the time series. $\sigma$ is the long-term standard deviation of variability, and $\tau$ defines a characteristic timescale where the PSD of this process breaks. We can relate this model to the structure function and the PSD in the following way:

$$SF^2(\Delta t) = 2\sigma^2_{\text{DRW}} \left[1 - e^{-\Delta t/\tau_{\text{DRW}}} \right], \quad \text{(A5)}$$

$$P(f) = \frac{4\sigma^2_{\text{DRW}} \tau_{\text{DRW}}}{1 + (2\pi f \tau_{\text{DRW}})^2}, \quad \text{(A6)}$$

where $P(f)$ is the PSD as a function of frequency $f$. By comparing Eqn. A5 and Eqn. A6, we have $\text{PSD}^2 = 2\sigma^2_{\text{DRW}}$ and $\text{ACF}(\Delta t) = \exp(-|\Delta t|/\tau_{\text{DRW}})$. This PSD follows white noise at low frequencies ($\propto f^0$), and transitions to a $f^{-2}$ PSD at higher frequencies below the characteristic timescale $\tau_{\text{DRW}}$.

In this study, we model our quasar light curves using the fast Gaussian process solver Celerite (Foreman-Mackey et al. 2017), which uses Gaussian process regression to fit the time series to a specified kernel. Given a number of terms in the kernel, and a method to maximize, Celerite can fit a time series to derive the best-fit parameters to said kernel. In our case, we utilize a DRW kernel (specified in Eqn. A4), as well as a term to characterize the effect of a white noise floor from unknown systematic flux errors ($\sigma_n$), also called jitter. We use uniform priors on all parameters within the input Celerite kernel (in log-space), and allow Celerite to minimize the log-likelihood in parameter-space to obtain a set of parameters to fit the light curve. We then use the MCMC sampler emcee (Foreman-Mackey et al. 2013) implemented in Python to draw from the joint posterior probability distribution output from Celerite. The final parameters compiled in the FITS table described in Table 1 are the median samples from these MCMC samples. The upper and lower errors for these parameters are obtained from the 16th and 84th percentiles of the samples. One example Celerite fit is shown in Fig. 5.

However, there are potentially additional features in the light curve that can skew the results of the DRW fit. Here, we investigate the effects of a long-term trend in the light curve on the recovery of $\tau_{\text{DRW,obs}}$ using Celerite and simulated data. We input simulated DRW light curves with input $\tau_{\text{DRW,obs}} = 100$ days, but add a long-term linear trend (non-stationarity) to the light curve, in this case of $1 \times 10^{-4}$ mag per day. We generate mock light curves using this hybrid model with different baselines, and use Celerite to extract a $\tau_{\text{DRW,obs}}$ from the simulated light curve. The results (shown in Fig. A1), show that as the baseline of the non-stationary light curve increases, the extracted $\tau_{\text{DRW,obs}}$ increases as well. In this test, the input $\tau_{\text{DRW,obs}}$ is 100 days, and is reasonably recovered for short baselines (less than ~ 10 years). However, as the baseline increases,
the linear long-term trend starts to skew the recovery of $\tau_{\text{DRW,obs}}$ towards longer and longer damping timescales.

A3 PSD Analysis with CARMA models

While many studies have shown that the DRW model can describe quasar light curve variability to a reasonable degree, we understand that it is not the only model available. It has been shown that stochastic processes generated from non-DRW models can be modeled with DRW (Kozłowski 2016a), albeit with biased DRW parameters. Therefore, to get a true sense of the PSD of quasar light curves and the stochastic processes occurring within their accretion disks, we utilize the more general CARMA model to obtain PSD measurements. Whereas DRW-modeled PSDs are restricted to having a white noise at low frequencies and a $f^{-2}$ PSD at higher frequencies (with a characteristic break timescale in between them), CARMA-predicted PSDs are not restricted to such a shape.

The PSD of a CARMA model is described in the following manner:

$$P(f) = \sigma^2 \left( \frac{1}{\sum_{k=0}^{p} \alpha_k (2\pi f)^k} \right)^2 \left( \frac{1}{\sum_{j=0}^{q} \beta_j (2\pi f)^j} \right)^2,$$  
\hspace{2cm} (A7)

where $\sigma^2$ is the variance of the modeled white noise process, $\alpha_j$ are the auto-regressive parameters of the model, and $\beta_j$ are the moving-average parameters of the model. The order of the CARMA model is defined by the $p$ and $q$ parameters, which define the number of auto-regressive and moving-average components respectively. The requirement that CARMA processes are stationary also requires that $q < p$. By convention, we set $\beta_0 = 1$ and $\alpha_1 = 1$. When setting $p = 1$ and $q = 0$, we recover the DRW PSD, as well as the covariance matrix, where $\tau_{\text{DRW}} = 1/\alpha_0$ and $\sigma_{\text{DRW}} = \sigma / \sqrt{\tau_{\text{DRW}} / 2}$. We use CARMA-pack to fit the quasar light curves to the DRW model, so we opt to utilize the widely used CARMA-pack code (Kelly et al. 2014) for our light curves to a generalized CARMA($p,q$) model. While the covariance matrix for the DRW model is somewhat simple, it becomes increasingly complex as the order of the CARMA model is increased, and therefore increasingly more complex to implement into Celerite. The generality of the kernel terms available in Celerite allows the implementation of a large variety in the kernels that can be used, but formulating the CARMA PSD in terms of Celerite’s kernel terms is highly involved. CARMA-pack also includes the functionality of choosing an optimal $(p,q)$ of the model used to fit the time series.

We perform the CARMA modeling using time series in the rest-frame of each quasar. To model our light curves to a generalized CARMA model with CARMA-pack, we obtain the optimal $(p,q)$ of the model. CARMA-pack does this by finding the maximum likelihood estimate of the CARMA model produced from a user-input grid of $(p,q)$ values. We choose to search a parameter space where $1 < p \leq 7$ and all $q < p$. After using 100 different optimizers initialized to random values for the CARMA parameters for a given model, the maximum likelihood estimate is chosen as the best-fit parameters for that model. This process is performed for a specified region in parameter space of $p$ and $q$, after which the code picks the $(p,q)$ combination which minimizes the corrected Akaike Information Criterion (AICC, Akaike 1973) provided by Hurvich & Tsai (1989). After choosing the optimal CARMA model for a given object, we use CARMA-pack to derive the maximum likelihood posterior distribution for all of the CARMA parameters. We then use CARMA-pack’s MCMC implementation to sample the CARMA parameters, given the order of the model. After testing the effect of the number of iterations of the MCMC on the convergence of fitted parameters (discussed in Appendix A4), we found the results are well convergent for 60,000 iterations and 30,000 burn-in samples. After running the MCMC sampler, CARMA-pack will then output samples for all of the CARMA parameters using the posterior distribution of the object’s fitted CARMA model. We can then use CARMA-pack to sample the PSD of the light curve given the fitted CARMA model, where we opt to use 10,000 samples. Similar to our structure function analysis, we use the median value of the CARMA parameters and PSD as the best-fit value, and the 16th and 84th percentiles of the samples to obtain the uncertainties in the values.

A4 Sampling Methods

One significant step in generating DRW and CARMA parameters for each light curve is the generation of samples from the posterior probability distribution through the use of MCMC sampling. In Celerite, this is done using the popular python-based MCMC sampler emcee, while the sampling in CARMA-pack is done through a custom, C++ MCMC sampler. One important parameter of sampling is the number of burn-in samples and actual samples to use for a given dataset. The burn-in samples for an MCMC sampler help to initialize the sampler to the data and allow it to converge properly. The number of actual samples for an MCMC sampler affects how well the posterior probability distribution for a parameter is sampled. For Celerite DRW fits, we opt to use 500 burn-in samples and 2,000 actual samples, which we found to be the optimal values through trial and error. For the CARMA-pack fits, we adjust the number of burn-in samples relative to the total samples as well as the number of total.
A5 Fitting simulated DRW light curves

Here we test if simulated DRW light curves with the same sampling and S/N as our real data would produce a steep high-frequency slope in the CARMA PSD. First, we generate mock $g$-band DRW light curves for all quasars in our sample using the best-fit $\tau_{\text{DRW, obs}}$ and $\sigma_{\text{DRW}}$ in §3.1. These mock light curves are sampled at the same times and with the same S/N as the real light curves in our sample.

Next, we use CARMA_pack to fit these mock DRW light curves with a generalized CARMA model following the same procedures described in Appendix A3. We then extract a PSD from each mock light curve from the best-fit CARMA model, and construct an ensemble PSD. The results are shown in Fig. A4, where we compare the PSDs from the expected DRW model and recovered by CARMA_pack.

We find that CARMA_pack successfully recovers a DRW PSD for these simulated light curves, as expected. This test confirms that the steep high-frequency-end PSD slope seen in real data is not due to effects of light curve cadence and S/N or the use of a more flexible CARMA model to fit the light curves.

We also use these simulated DRW light curves to investigate different choices of the best-fit parameters in Celerite or CARMA_pack. In this work, we opt to use the median of the posterior distribution of samples as the fiducial best-fit parameters for all DRW and general CARMA model fits. Other works may use different choices for their best-fit parameters (such as the maximum-a-posteriori (MAP) (MacLeod et al. 2010) or the expectation value of the marginalized posterior (Suberlak et al. 2021)). Here, we discuss the differences in these choices of the best-fit parameters.

When modeling our quasar light curves with Celerite or CARMA_pack, we are given a number of samples for each parameter, output by a certain MCMC algorithm. The posterior probability distribution is simply the normalized distribution of the output parameters themselves. Using the median of the posterior is less susceptible to large fluctuations in the probability due to insufficient sampling of the distribution. The MAP, however, can prove to be unreliable, as it can be easily influenced by these fluctuations. The marginalized posterior utilizes the joint-posterior distribution of multiple parameters, giving a more robust look into the relationships between parameters, and taking that into account to choose the best possible value. The expectation value of this distribution (as opposed to the MAP or median) can aid if the posterior distribution has multiple peaks.

We compare different choices, including: median posterior, MAP, and expectation value. Both the MAP and the expectation value of a parameter’s distribution are obtained by using the marginalized distribution of each parameter. This is done through the use of the likelihoods output from the Celerite fitting, for each quasar. One of the functions implemented in Celerite allows one to obtain a likelihood for a given set of parameters and data, given the model fit to a certain set of data. Therefore, for each sample from a given quasar...
light curve fit, we can construct a grid in parameter space, performing this likelihood calculation for an arbitrary number of points to obtain an n-dimensional posterior distribution, where n is the number of parameters. In this case, Celerite fits for both DRW parameters and a noise term, making this posterior three-dimensional. We can then marginalize over this distribution for each of the parameters, and obtain a best-fit parameter for each light curve.

We compare these different choices of best-fit parameters in Fig. A5. We obtained these values from fitting our simulated DRW light curves with a DRW model with Celerite, as well as CARMA_pack (in the latter case, a DRW or CARMA(1,0) model is enforced). We find that all these choices perform similarly for both DRW parameters with a similar amount of scatter, when compared to the input DRW parameters used to construct the simulated light curves. Overall, $\sigma_{DRW}$ is better recovered than $\tau_{DRW, obs}$. For long input $\tau_{DRW}$, the recovered $\tau_{DRW}$ is generally biased low due to an insufficient baseline of the light curve (e.g., Kozłowski 2017). Interestingly, the median posterior from the Celerite fit produces the least overall bias in $\tau_{DRW}$ for our sample, justifying our choice of this particular definition of best-fit DRW parameters in this work.

Fig. A6 shows the comparison of the three different choices of the best-fit DRW parameters, using Celerite for the same simulated DRW light curves described above. While there are correlations among these different choices, there are also systematic offsets among them. For this study, we have chosen the median posterior as our fiducial best-fit parameters, given its performance in recovering the input DRW parameters as demonstrated in Fig. A5.

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Figure A5. Comparison of the recovered and input DRW parameters ($\tau_{\text{DRW, obs}}$, $\sigma_{\text{DRW}}$) from our test using simulated DRW light curves. The best-fit value for the recovered parameter was obtained via three different methods: (1) the MAP from Celerite fitting samples, (2) the expectation value of the marginalized posterior using Celerite fitting samples, (3) the median value of the Celerite fitting samples, and (4) the median value of the CARMA_pack DRW fits samples. For each panel, the unity relation is shown as a red line.

Figure A6. Comparison of different choices of the best-fit DRW parameters in Celerite, obtained from our simulated DRW light curves. These $\tau_{\text{DRW, obs}}$ and $\sigma_{\text{DRW}}$ values are determined using the same sets of posterior samples. The method used to obtain these MAP values and expectation values uses the marginalized posterior distribution of the samples. The red line in each panel indicates the unity relation.