Photometric Monitoring of Quasars with Kepler

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Abstract:

We have used *Kepler* photometry to characterize variability in four radio-loud active galactic nuclei (AGN; three quasars and one object tentatively identified as a Seyfert 1.5 galaxy) on timescales from minutes to months, comparable to the light crossing time of the accretion disk around the central supermassive black hole or the base of the relativistic jet. *Kepler*'s almost continuous observations provide much better temporal coverage than is possible from ground-based observations. We report the first such data analyzed for quasars. We have constructed power spectral densities using eight *Kepler* quarters of long-cadence (30-minute) data for three AGN, six quarters for one AGN and two quarters of short-cadence (1-minute) data for all four AGN. On timescales longer than about 0.2–0.6 days, we find red noise with mean power-law slopes ranging from −1.8 to −1.2, consistent with the variability originating in turbulence either behind a shock or within an accretion disk. Each AGN has a range of red noise slopes which vary slightly by month and quarter of observation. No quasi-periodic oscillations of astrophysical origin were detected. We detected flares of several days long when brightness increased by 3%–7% in two objects. No flares on timescales of minutes to hours were detected. Our observations imply that the duty cycle for enhanced activity in these radio-loud AGN is small. These well-sampled AGN light curves provide an impetus to develop more detailed models of turbulence in jets and instabilities in accretion disks.

Objective:

The goal is to understand the origin of optical variability in blazars. Light curves can provide important clues to the dominant processes (**Figure 1**). We want to see if some variability is due to a bright feature in the accretion disk as it approaches the last stable orbit, or if it is due to inhomogeneities in the jet, possibly in a helical structure (**Figure 2**).

Methodology:

We monitored 4 quasars (**Table 1**) continuously with *Kepler* for two years, generating some of best-sampled quasar time series ever recorded. Each quarter yielded ~4,300 30-minute samples (for example, **Figure 3**). Power Spectral Densities (PSDs) were generated for each object, for each quarter separately (Table 2). We used raw *Kepler* data, because the standard pipeline product that removes day-to-week-scale drifts (required for planet detection) also removes real astrophysical brightness variations. We did not stitch quarters together, but analyzed the individual quarters separately. Combining quarters to study longer-term variability requires careful removal of steps between quarters, and the residual effect of differential velocity aberration (visible as an instrumental trend in **Figure 3**). We have deferred analyzing the data for long term trends because they require special treatment still under development. **Figure 4** shows an example of the editing and calibration steps performed on the light curves.

The four flat-spectrum radio quasars we monitored for 2 years with *Kepler* showed low-amplitude variability. One significant flare of 5% amplitude was detected. PSDs were generated for each quarter of data (as discussed in poster 339.02); **Figure 5** shows four examples. We computed power spectral densities for each quarter of data (**Table 2**) with slopes ranging from -1.2 to -1.8. There is evidence for slope differences of 0.2-0.3 between targets, and for variations from quarter to quarter.

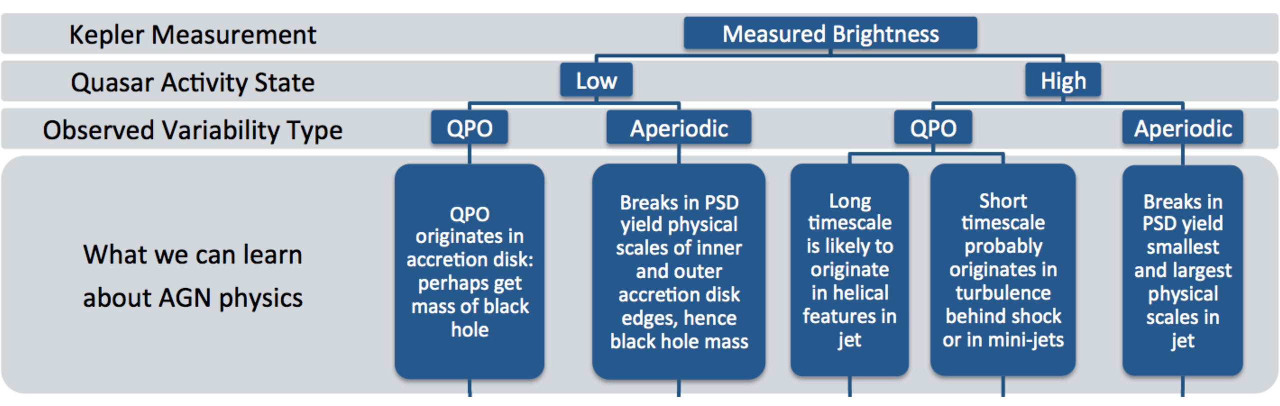

Figure 1: Optical variability provides clues to the origin of the optical emission from the quasar nucleus. Several possibilities can be explored, depending on the quasar activity state and periodicity (or lack thereof) in the light curve.

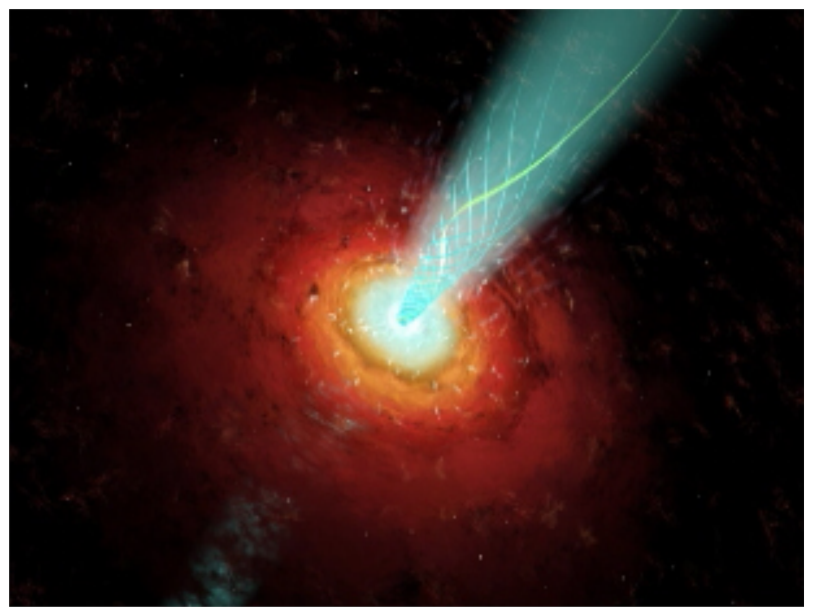

Figure 2: Quasar optical continuum emission comes from an accretion disk and relativistic jet. Variability in the fluxes from these components is indicative of the location of the emission (angular scale is of order milliarcseconds)

Table 1: *Kepler* target list; objects are designated A-D for convenience

Object Designation	Name	Kepler Input Catalog Number	Right Ascension (hh:mm:ss.s)	Declination (dd:mm:ss)	Kepler Input Catalog Magnitude	Redshift	Radio Spectral Index[a]
A	MG4 J192325+4754	10663134	19:23:27.24	47:54:17.0	18.6	1.520	0.32
B	MG4 J190945+4833	11021406	19:09:46.51	48:34:31.9	18.0	0.513	0.75
C	CGRaBS J1918+4937[b]	11606854	19:18:45.62	49:37:55.1	17.8	0.926	0.00
D	[HB89] 1924+507	12208602	19:26:06.31	50:52:57.1	18.4	1.098	0.19

Notes.
[a] Radio spectral index obtained from VLBA Calibrator Web site, defined between 2.3 and 8.3 GHz or 2.3 and 8.6 GHz with $S \propto \nu^{-\alpha}$.
[b] The Kepler Input Catalog incorrectly indicates that this target is a star with contamination 0.73, but we have verified it as an isolated quasar.

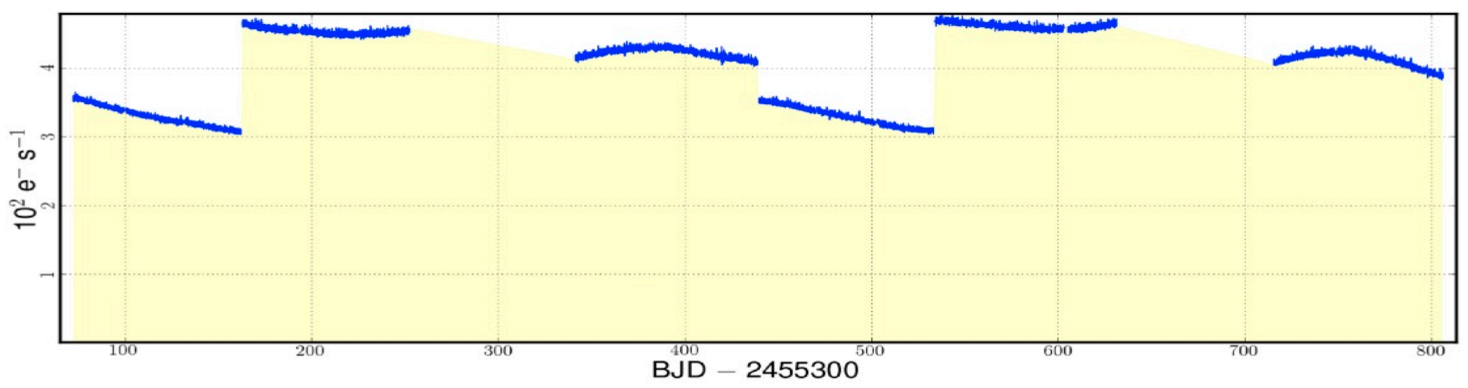

Figure 3: *Kepler* raw data for Object B, showing Q6-13 data (except Q8 and Q12, due to an inoperable detector). There is no dominant astrophysical trend here. All step function changes are due to changes in the photometric aperture with each quarterly roll. The slow variation within each quarter (in this object) is due to differential velocity aberration. Data from each quarter was fitted with a combination of red and white noise (see **Figure 5** and **Table 2**).

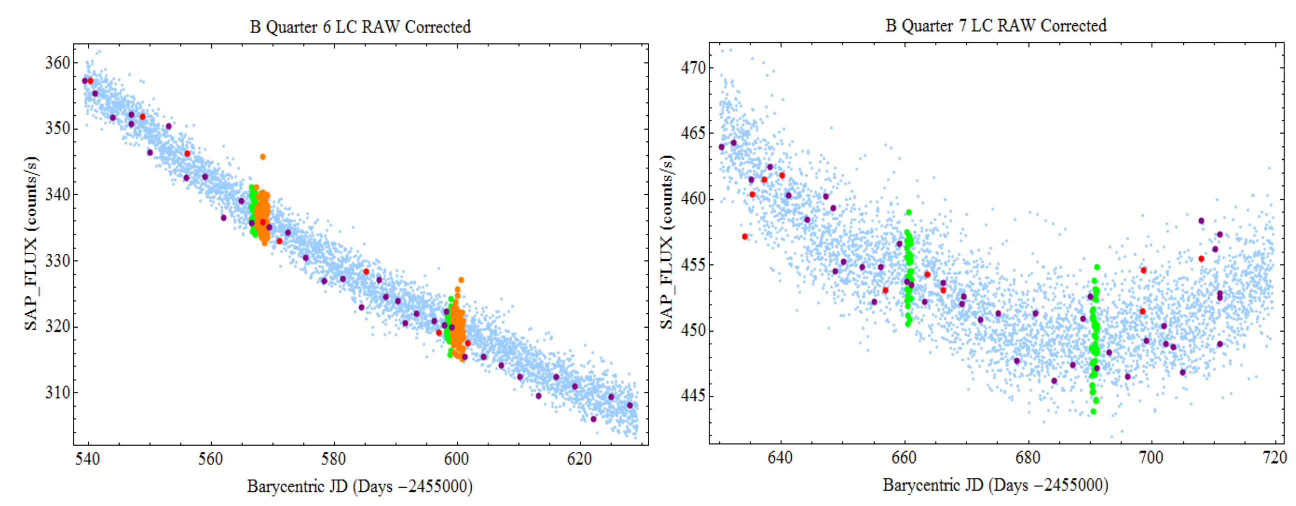

Figure 4: Corrected light curves for Object B for the first two quarters (Q6, Q7), after removal of outliers and monthly thermal transients, etc. They illustrate the long almost unbroken run of data that enables us to generate reliable PSDs.

Summary:

We have observed three FSRQs and one radio-loud AGN (tentatively classed as a Seyfert 1.5 galaxy) for 2 yr with *Kepler*. We find PSDs in the light curves that vary from source to source and quarter to quarter for the same source, ranging from α = −1.2 to −1.8. We find several clear, isolated flares over a few percent amplitude which are of astrophysical origin. We do not detect any of the expectedly rare QPOs as could be generated by ADs or helical jet features. The PSDs measured agree with models for the observed variability originating in turbulence behind a shock in the jets or in the ADs. These observations present beautiful sets of high quality data. Future work on combining data across quarterly boundaries and extending the observations for the life of the *Kepler* mission could provide us with estimates of the largest relevant scales of the physical processes producing the variability. With the further development of shocked jet models including turbulence (e.g., A.P. Marscher 2013, in preparation), these types of continuous light curves may distinguish between jet turbulence and AD fluctuations as the dominant source of quasar optical variability.

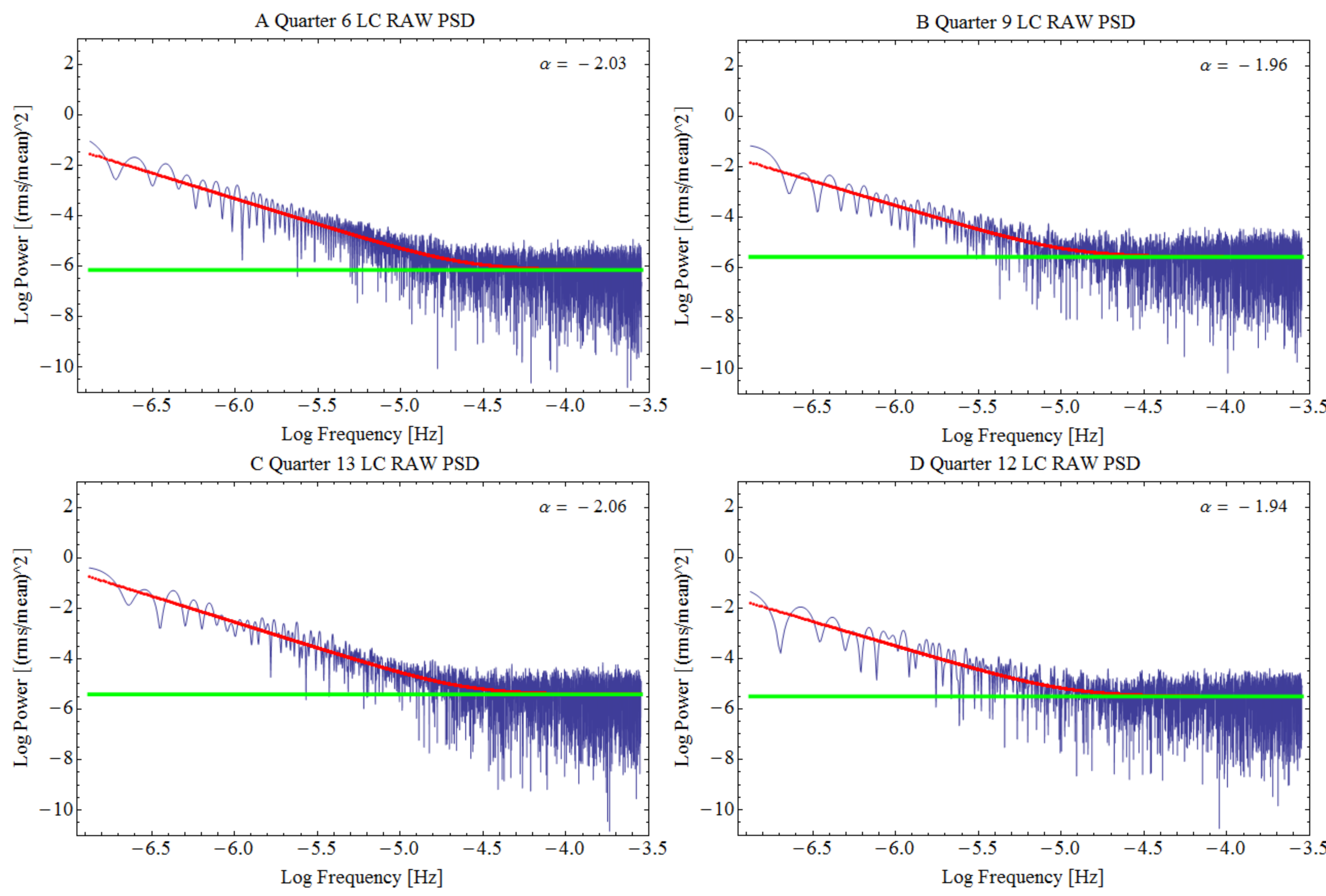

Figure 5: Power Spectral Densities (PSDs) for one quarter for each of the 4 quasars we observed, showing the decomposition into a high-frequency white-noise component, and a power law-component at frequencies below about 10^{-5} Hz (1.3 days). Fitted slopes for all of the long-cadence data are summarized in **Table 2** below.

Table 2: AGN Variability Power Spectral Densities (PSDs) Measured with Long-cadence *Kepler* Data

				SAP (Raw) Data		Corrected SAP Data	
Object Designation	*Kepler* ID	Quarter	Moiré Level	Slope (Original)	Slope (End-matched)	Slope (Original)	Slope (End-matched)
A	10663134	6	Medium	−1.9	−1.7	−2.0	−1.6
A	10663134	7	High	−2.1	−2.1	−2.3	−1.3
A	10663134	8	None reported	−2.0	−1.9	−2.1	−2.0
A	10663134	9	High	−1.7	−1.3	−1.6	−1.4
A	10663134	10	Medium	−1.5	−1.6	−1.6	−1.4
A	10663134	11	High	−2.0	−1.7	−2.1	−2.0
A	10663134	12	None reported	−1.8	−1.9	−2.0	−1.8
A	10663134	13	High	−1.9	−1.7	−1.8	−1.8
Mean[a]				−1.8	−1.8	−1.9	−1.7
SD				0.2	0.2	0.2	0.3
B	11021406	6	None reported	−1.9	−1.6	−2.0	−1.4
B	11021406	7	None reported	−1.8	−1.3	−1.9	−1.2
B	11021406	8	None reported	···	···	···	···
B	11021406	9	None reported	−1.5	−1.7	−1.8	−1.8
B	11021406	10	None reported	−1.8	−1.0	−1.5	−0.9
B	11021406	11	None reported	−1.6	−1.7	−1.8	−1.3
B	11021406	12	None reported	···	···	···	···
B	11021406	13	None reported	−1.8	−1.6	−1.9	−1.7
Mean				−1.7	−1.5	−1.8	−1.4
SD				0.2	0.3	0.2	0.3
C	11606854	6	None reported	−1.9	−1.4	−2.0	−1.6
C	11606854	7	Medium	−1.5	−1.9	−1.6	−2.0
C	11606854	8	None reported	−1.8	−1.2	−2.0	−1.6
C	11606854	9	None reported	−1.9	−1.9	−1.9	−2.0
C	11606854	10	None reported	−1.9	−2.4	−2.1	−2.1
C	11606854	11	Medium	−1.8	−2.0	−2.0	−2.0
C	11606854	12	None reported	−1.8	−1.7	−1.9	−1.7
C	11606854	13	None reported	−1.8	−2.0	−2.0	−2.0
Mean				−1.9	−1.8	−2.0	−1.8
SD				0.1	0.4	0.1	0.2
D	12208602	6	Medium	−1.8	−1.5	−1.9	−1.3
D	12208602	7	None reported	−1.4	−1.2	−1.5	−1.0
D	12208602	8	None reported	−1.0	−0.8	−1.2	−0.8
D	12208602	9	None reported	−1.9	−1.6	−2.0	−1.6
D	12208602	10	Medium	−2.0	−1.4	−2.0	−1.4
D	12208602	11	None reported	−1.9	−1.3	−1.8	−1.4
D	12208602	12	None reported	−1.5	−1.2	−1.8	−0.9
D	12208602	13	None reported	−1.1	−1.2	−0.7	−1.3
Mean				−1.5	−1.2	−1.5	−1.2
SD				0.4	0.2	0.5	0.3

Note. [a] Means and standard deviations computed using only quarters with no Moiré reported, except for A, for which Q6 and Q10 were also included.

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