AGN variability studies with the repurposed Kepler mission

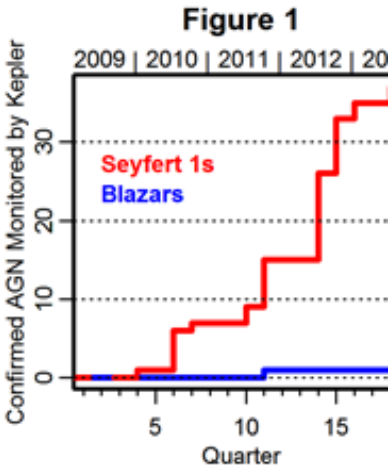
R. Edelson, R. Mushotzky, M. Malkan, S. Vaughan, K. Horne

Abstract: We present a strategy to identify and gather light curves for dozens of AGN concurrent with the main observations of a repurposed Kepler mission. These parallel observations only require modest telemetry resources and will not affect where the telescope is pointed. Thus the repurposed mission will continue to gather light curves that probe AGN variability on shorter timescales than any other telescope, enhancing our picture of the physical conditions close to the supermassive black hole.

1. Introduction: Kepler's contribution to our picture of AGN variability

Kepler produces unparalleled optical light curves, with fast (30 min) sampling, high (>90%) duty cycle, and excellent precision (~0.1% for a ~15th magnitude source), covering a baseline of years. Although variability is one of the most physically constraining observed properties of active galactic nuclei (AGN), only one AGN, Zw 229-15, was observed during Kepler's first year of operation.

In order to fully exploit Kepler's potential impact on AGN variability, our group undertook an intensive effort to identify and monitor AGN in the ~115 sq. deg. Kepler field. We first performed an intensive catalog search to identify and initiate Kepler monitoring of six additional AGN in Cycle 2 (starting in Quarter 6; Q6). We then devised the "W2R" technique that uses archival WISE, 2MASS and Rosat data to identify highly likely AGN candidates (Edelson & Malkan 2012) solely on the basis of existing all-sky survey data. This allows one to construct a sample of AGN in any sufficiently large region of sky, including the previously sparsely surveyed Kepler field near the Galactic Plane. We identified the Kepler AGN candidates and requested they be added to the Kepler download list via the normal AO process as well as the DDT process when candidates were identified mid-cycle. All AGN candidate identifications were tested with spectra from the Lick 3-m Kast spectrograph. As shown in Figure 1 (right), this intensive effort led to a rapid increase in the number of confirmed AGN that were observed by Kepler, so the archives contain a total of 37 AGN with more than one quarter of data. This includes W2R1926+42, the only rapidly variable BL Lac object known to be monitored by Kepler (see Figure 2).



Sadly, our strong focus on identification and download of data for as many AGN as possible instead of immediate scientific exploitation of the early data on just a few sources was vindicated when the second reaction wheel failed in Q17: in spite of this disaster, the Kepler archives safely contain light curves for dozens of AGN for which data would not otherwise have been recorded. Even more important going forward, we now have a proven method that allows us to identify bright AGN ***anywhere*** that Kepler is pointed.

2. Proposed work

This white paper proposes to use the Edelson & Malkan (2012) W2R technique to identify bright (J < ~16) AGN in whatever field(s) the repurposed mission ultimately observes. Since

that paper finds 4316 AGN or highly likely (~95% confidence level) AGN candidates across the entire sky, a typical ~115 sq. deg. Kepler field will contain of order a dozen bright W2R AGN/AGN candidates.

Once NASA announces the target fields for the repurposed mission, we will select all W2R sources on Kepler silicon in each field. We will also use standard catalogs (e.g. Veron-Cetty & Veron 2010) to find additional bright AGN missed by the W2R technique. We expect that in combination these two approaches should yield ~12-20 bright AGN on silicon in each field that Kepler points at. For every identified target AGN, we will build masks in conformance with current guidance and communicate this information to the Kepler GOF so that its data can be downloaded. Thus our request will only be for for telemetry resources to download these pixels; we will not request that Kepler be pointed at any specific source or field.

Note that a larger number of AGN were observed in the nominal mission because we pushed to fainter limits and outside of the original infrared cutoffs to identify more AGN. That higher false detection rate was acceptable because we took the additional step of confirming all candidates at Lick. This will not be done for the repurposed mission because the lifetime is expected to be shorter and because Kepler will telemeter down fewer than the ~165,000 targets downloaded during the nominal mission. On the other hand most target fields will be at higher Galactic latitudes than the original Kepler field, many will have been subjected to much deeper AGN surveys, so we expect to request downloads for ~12-20 AGN in each new Kepler field.

3. Science goals

Because AGN are much too distant to image directly except via gravitational lensing, indirect methods such as variability must be used to constrain the physical processes at work in their centers. Until Kepler, progress in the optical had been slowed by limitations inherent in ground-based monitoring: it is difficult or impossible to obtain continuous light curves longer than ~12 hr and with errors better than ~1%. Kepler provided the first AGN light curves with fast, continuous sampling, high duty cycle, and excellent precision, covering a baseline of years (see Figures 2 and 3), allowing a more detailed and accurate picture of rapid variability in AGN (see, e.g., Mushotzky et al. 2011, Carini & Ryle 2012, Edelson 2013a,b, Horne et al. 2013). Below we discuss some scientific problems that could be better addressed by enlarging the number of AGN Kepler observes in the repurposed mission.

3.1. Probing Seyfert 1 accretion disk physics with Kepler monitoring

The physical processes driving the strong, ubiquitous optical variability seen in AGN are poorly understood at present, but the strongest candidates are "internal" fluctuations in local accretion rate and "external" heating of the disk by coronal X-ray radiation. The natural time scales of interest range from the light-crossing timescale ($t_{lc} \sim 3\ M_7\ R_{100}$ hours) to the viscous (radial drift) timescale ($t_{visc} \sim 3\ M_7\ R_{100}^{3/2}\ (h/r)_{0.1}^{-2}\ \alpha_{0.1}^{-1}$ years; where M_7 is the black hole mass in units of 10^7 solar masses, R_{100} is the emission distance in units of 100 times the Schwarzschild radius $r_g = 2GM/c^2$, $\alpha = 10*\alpha_{0.1}$ is the standard Shakura-Sunyaev [1973] viscosity parameter and $(h/r) = 10*(h/r)_{0.1}$ is the scale height/radius of the disk; Frank, King & Raine 2002). Simple scaling arguments (e.g. Shakura & Sunyaev 1976) imply that to first order all characteristic time scales should scale with the black hole mass, and accretion disk theory predicts additional dependence on accretion rate and other parameters. And if the emission is relativistically beamed, the observed timescales shrink by the Doppler factor.

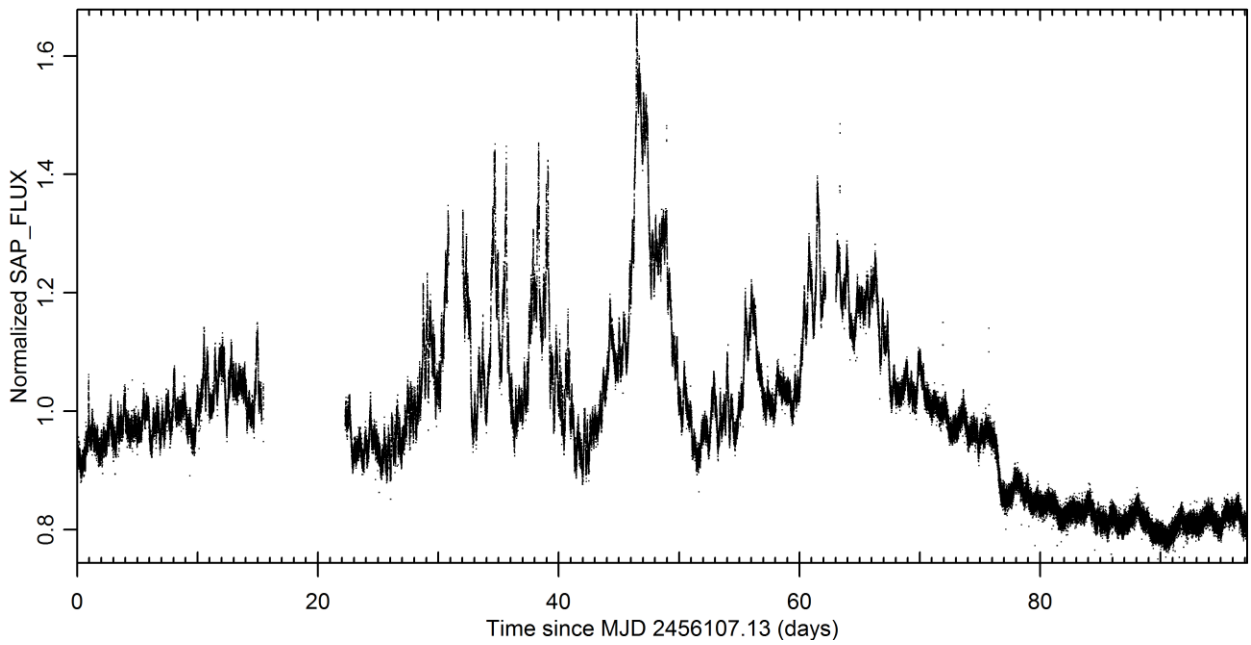


Figure 2a: Q14 Kepler SC light curve for W2R1926+42, sampled every ~1 minute with a ~90% duty cycle over a ~3 month period. Errors are not plotted. The gap on days ~16-22 is due to a coronal mass ejection event. The normalization is different than the Q11/12 analyzed in Edelson et al. (2013a) so these data appear to extend below the 88% floor. This light curve contains 128,940 points so no single panel figure can convey the full extent of available information.

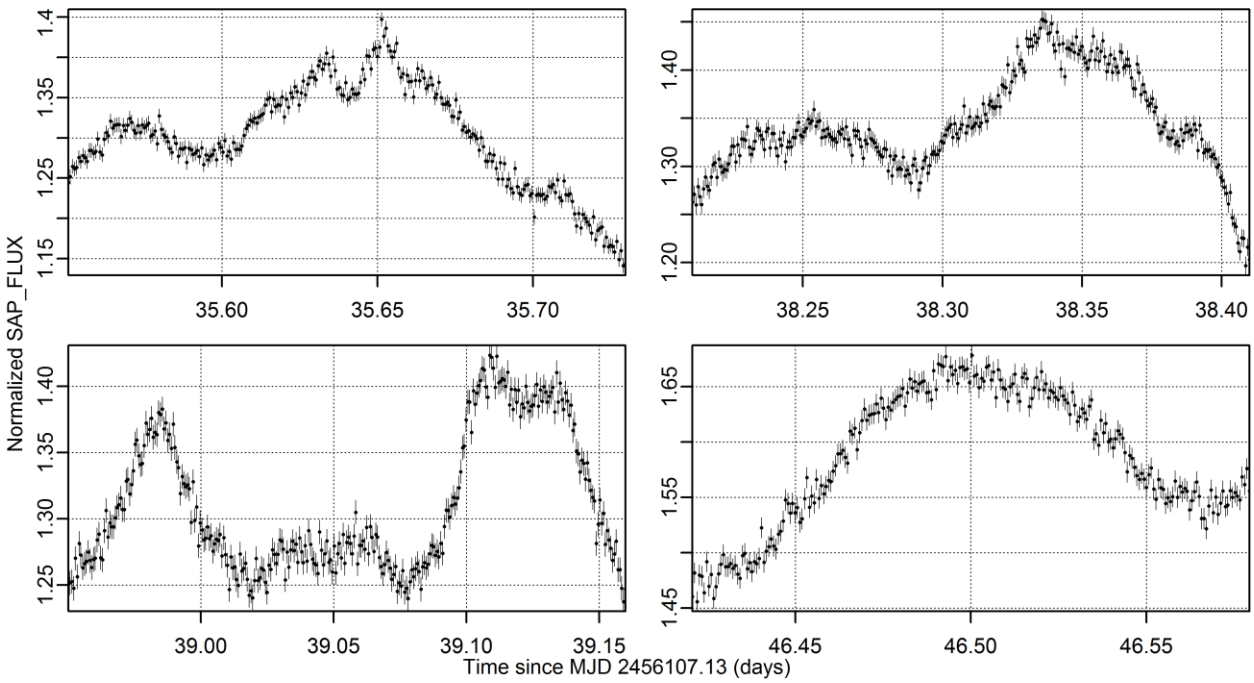


Figure 2b: Short (~4-5 hr) sections of the above Kepler light curve, indicating the unprecedented level of coverage and detail available in these data. For instance the clear separation of the peaks at ~38.98 and ~39.11 days is not discernible in Figure 2a. Errors (1σ) are shown in this plot. These light curves exemplify the high duty cycle, sampling, and precision AGN data that can currently only be obtained with Kepler.

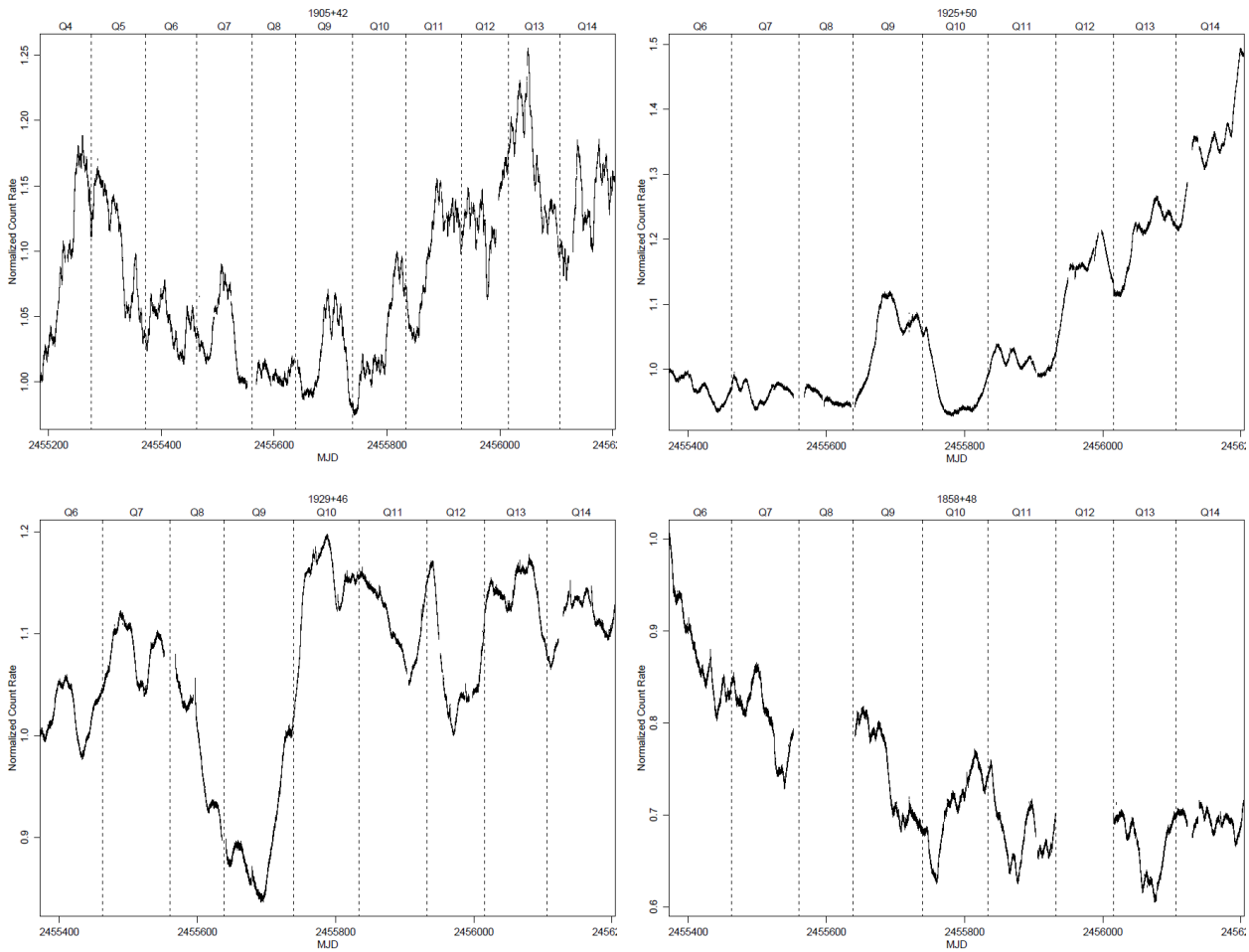


Figure 3: Kepler light curves of 4 confirmed Seyfert 1 galaxies. SAP_FLUX data were normalized so that the first point has a value of 1, and simple additive scaling was used to match data across the gaps between quarters (dashed lines). Note that the last AGN, 1848+58 is missing every fourth quarter of data when it fell on the bad module #3. Although the repurposed mission light curves will not have this duration, they should have similar (>~90%) duty cycles and the S/N should be at least as good from the ground, allowing us to probe time scales of tens of hours to days that could otherwise never be accessed.

The "propagating fluctuation" model (Lyubarskii 1997, King et al. 2004, Arévalo & Uttley 2006) posits that the variations are generated internally by random variations in viscosity (and therefore local accretion rate) over a wide range of spatial scales in the accretion flow. Variations at different radii modulate the mass inflow, and those at the inner, luminous regions are driven by coupled variations propagating in from all spatial scales on the (viscous) radial drift time.

Radiation from the non-thermal x-ray-emitting corona thought to be immediately surrounding the black hole must, at some level, heat the disk, providing an alternative external source of optical variability. The predictions of this "reprocessing" scenario are consistent with the observed lags between long and short optical wavelength variations (Cackett et al. 2007).

Prior to Kepler, optical PSDs estimated from relatively sparsely-sampled data suggest flat slopes with a spectral index $\alpha \sim -2$ (Arévalo et al. 2009) to -1.4 (Breedt et al. 2010). Kepler single-quarter light curves (Mushotzky et al. 2011) yield much better-determined optical PSDs

that indicate the slopes are much steeper ($\alpha \sim -3$) power-laws with no evidence of a break up to time scales of weeks. Such steep slopes are inconsistent with the "damped random walk" model (Kelly et al. 2009), which predicts a high-frequency slope of –2. We find that these steep slopes generally continue to longer timescales when multiple quarters are combined.

The next crucial step is to enlarge the sample to cover a wide range of source properties such as luminosity and black hole mass. We will improve upon the initial Mushotzky et al. (2011) sample of 4 nearby ($z < 0.1$) objects (see also Figure 3) as well as the current sample of 38 AGN (e.g. Edelson et al. 2013b) by adding dozens more AGN. This will allow us to test correlations between PSD properties (such as the characteristic time scale) and the primary AGN characteristics M_{BH}, L, z, etc. and test the predictions of accretion disk theories.

Kepler monitoring also provides the best opportunity for the search and characterization of any quasi-periodic oscillations (QPOs) in AGN, or for ruling out their existence. Only one AGN QPO is known so far (Gierlinski et al. 2008; in X-rays), and discovering one in the optical would be a landmark discovery by Kepler. These can be searched for using specialized QPO detection algorithms (e.g. Vaughan 2010).

3.2. BL Lac "microvariability"

The discovery by Edelson & Malkan (2012) of the rapidly-variable Kepler BL Lac W2R1926+42 has led to the highest quality optical light curve ever obtained for a BL Lac (see Figure 3), and possibly in many respects the best ever obtained for any AGN at any frequency. Our preliminary analysis already shows new, heretofore unseen phenomena (Edelson et al. 2013a). The Kepler data for this source demonstrate that phenomenon of blazar "microvariability" (so-called on the basis of ~8-12 hr ground-based observations) is real, and that it consists of periods of strong flaring and relative quiescence. These data are so rich (in terms of sampling, duty cycle, and ratio of variability to noise) that we were unable to fit the resulting PSD estimate with any of the simple models that have been proven successful for Seyfert 1s (see above). The best fitting models suggest a power-law that bends from $\alpha \sim -2.8$ to -1.9 at a temporal frequency corresponding to ~4 hr. This is a much shorter timescale than seen in Seyfert 1s and is the first such break clearly detected in a BL Lac object. We also find that the flux distribution is close to a lognormal distribution, and that the rms/flux relation may be non-linear, the first such observation in any source. While it is premature to say that we fully understand them, these data do make it clear that Kepler's extraordinary sampling and precision have the capability to dramatically advance our understanding of blazar astrophysics.

The Edelson & Malkan (2012) W2R technique can identify both Seyfert 1s/quasars and the rarer BL Lac objects, as evidenced by the fact that the BL Lac W2R1926+42 was found by that method. This is in large part because both types of AGN have infrared continua which are close to power-law in shape, as is the 2MASS/WISE infrared color template. Thus we might be able to identify BL Lac objects in the new fields that Kepler observes as well. A second such source with extraordinary Kepler data would allow us to begin to probe the range of optical variability seen in beamed AGN.

4. Technical details

4.1. Observing modes

The repurposed Kepler mission is expected to utilize a "point-drift" mode in which the satellite slowly but predictably drifts by ~1.4 degrees over a 4 day period. Thus a given source appears to follow a predictable arc across the detector. We expect that the project will determine the best way to download such data: either creating moving download windows that follow the source motion across the detector, or downloading the entire arc and then just analyzing the relevant target pixels in each cadence. The first approach has the advantage of minimizing telemetry requirements while the second would not require the creation of new flight software. No matter which mode is ultimately chosen, we will provide whatever masks or other information is needed to accomplish these observations.

4.2. Support observations

The quality of the AGN light curves from the nominal mission motivated a series of multi-wavelength support observations to further enhance their value. Two Kepler AGN (Zw 229-15, Barth et al. 2011; and W2R1858+48) have been subjected to ground-based optical emission line "reverberation mapping" campaigns by the Lick 3-m AGN Monitoring Program with nearly complete nightly spectroscopic coverage for ~75 consecutive nights. Zw 229-15 has also been monitored by Spitzer (Gorjian et al. 2012) and in the X-rays by Swift and Suzaku. We are preparing our paper on the X-ray/Kepler campaign (Horne et al. 2013). The BL Lac object 1926+42 is being monitored at 15 GHz by the Ryle Telescope in the UK, and we have requested VLBA time to make a map of it.

Depending on the nature of the repurposed mission (e.g. long-duration monitoring of one or two fields vs. short looks at a larger series of fields), we will undertake whatever simultaneous multiband monitoring is appropriate to further enhance the value of these data.

4.3. Relevance to NASA astrophysics objectives

This research is relevant to NASA's astrophysics goals as it addresses the question "How do matter, energy, space, and time behave under the extraordinarily diverse conditions of the cosmos?" The study of AGN supermassive black hole/accretion disk systems allows us probe the physics of matter at densities and conditions that could never be duplicated on Earth.

5. References

Arévalo, P. & Uttley, P. 2006, MNRAS, 367, 801
Arévalo, P. et al. 2009, MNRAS, 397, 2004
Barth, A. et al. 2011, ApJ, 732, 121
Breedt, E. et al. 2009, MNRAS, 394, 427.
Cackett, E. et al. 2007, MNRAS, 380, 669
Carini, M. & Ryle, W. 2012, ApJ, 749, 70
Edelson, R. et al. 2013a, ApJ, 751, 52
Edelson, R. et al. 2013b, in preparation
Edelson, R. & Malkan, M. 2012, ApJ, 751, 52
Frank, J., King, A, Raine, D. 2002, "Accretion Power in Astrophysics: 3rd Ed." Cambridge
Gierlinski, M. et al. 2008, Nature, 455, 369
Gorjian, V. et al. 2012, BAAS, 219, 154.13
Horne, K. et al. 2013, in preparation
Kelly, B. et al. 2009, ApJ, 698, 895
King, A. et al. 2004, MNRAS, 348, 111.
Lyubarskii, Y. 1997, MNRAS, 292, 679.
Mushotzky, R. et al. 2011, ApJL, 743, L12
Shakura, N. & Sunyaev, R. 1973, A&A, 24, 337
Shakura, N. & Sunyaev, R. 1976, MNRAS, 175, 613
Uttley, P. et al. 2002, MNRAS, 332, 231
Vaughan, S. 2010, MNRAS, 402, 307
Véron-Cetty, M.-P., Véron, P. 2010, A&A, 518, 10