Extragalactic Science with Kepler in two Gyro Mode, a White Paper

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Abstract

This white paper is a respons to NASA's *"Call for White Papers: Soliciting Community Input for Alternate Science Investigations for the Kepler Spacecraft." W*e describe what the monitoring of small galaxies with Kepler can do for supernova explosions, exotic transients, and Active Galactic Nuclei and other blackhole phenomena,.

Kepler's results on extragalactic astrophysics, while less well known than the planetary discoveries are, just as exciting. Early results on active galactic nuclei (AGN) (e.g., Mushotzky et al, 2011, Edeleson et al 2013,) have explored AGN variability on a wide variety of timescales from hours to months. Another program, targeting just ~400 galaxies, is not only finding many new AGN (Olling etal 2013b) at much lower levels of activity than have been found heretofore, but has also discovered a number (>4) of likely supernova (SN) candidates, providing, for the first time, constant coverage months before the event, through the rise, and for many months afterwards (Olling etal, 2013a). Extra-galactic science has benefited from the monitoring of a few hundred galaxies with Kepler, and can be revolutionized with the monitoring of thousands of galaxies.

A strawman "Kepler Extragalactic Survey," or KES, would comprise one year of Kepler observations of about 20,000 galaxies and a few hundred normal AGN, perhaps split over 6 or so fields in the sky, with the specific aim of searching for and identifying SNe and low-variability AGN. We propose to monitor bright galaxies (m <19) to search for extra-galactic variability and transients. Given the result from our Kepler GO programs, we expect this study to discover and provide light curves with unprecedented detail of ~140 SNe. In addition, we would identify ~2,000 low-variability AGN candidates and study known AGN in the fields chosen. There are no existing or planned facilities that could observe SN explosions as well as Kepler, even in two gyro mode.

Every Kepler transient should be promptly detected by our ground-based survey and follow-up resources can be brought to bear. Thus, we will be able to combine the full value of ground-based surveys: colors, spectra, wide area context, classification, with the exquisite light curves that will be downloaded from Kepler. The combination promises to create a "gold standard", unbiased set of

transient sources that can serve many different science projects.

Introduction

From our Kepler GO galaxy observations, we determine a SN rate of about 0.7 SNe per century, per galaxy and we find that of order 10% of galaxies hosts low-level AGNs. We believe that the precision in such a study would be insignificantly impacted by Kepler’s loss of a reaction wheel.

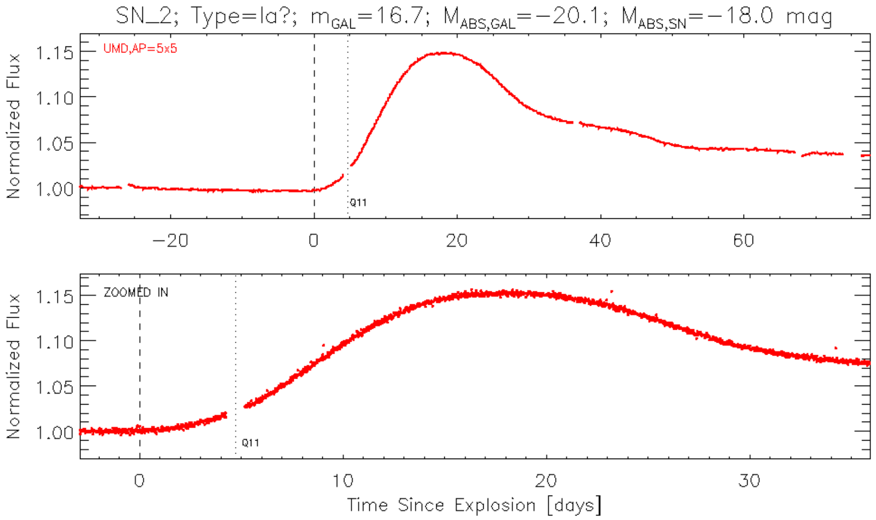


Figure 1: Light curve of one the transients detected in our Kepler GO data. The transient is photometrically classified as a Type Ia. Spectra of the host galaxy yield a redshift of 0.05. No obvious shock break-out is detected in the early light curve (before maximum), which is hint of the possible progenitor. Subtle, long-term features (like the secondary plateau at t ~40 days) are clearly visible. The light curve in the top panel is smoothed on a timescale of 1/3 day. The bottom panel shows the individual data points. This light curve is derived with our own specialized software that achieves long-term photometric stability. The gaps are due to downlink periods.

Kepler has *four capabilities* that can provide extraordinary detailed variability studies of both AGN and SNe: 1) high observing cadence: one exposure every 30 minutes, 2) long, almost uninterrupted ob-serving spans (years) 3) excellent sensitivity (0.01 mag at V~18) per ½ hour observation, and 4) a huge field of view. The combination of all four of these capabilities in one observatory is unique to Kepler.

Ground and space-based surveys can have some but not all of these capabilities. Ground based project can match the high cadence through a night, but are interrupted by the rising sun and also weather issues. Some space based observatories have three of these capabilities, like NASA's STEREO, but that only goes down to V~12. We believe that even with Kepler's reduced capabilities, it will retain sufficient photometric accuracy to accomplish major science goals in the areas of SN and AGN research. And when tied together with vibrant ground based support, the combination cannot be beat.

An Extragalactic Survey

Our strawman “Kepler Extragalactic Survey” of 20,000 galaxies would last for about a year . Given our data reduction procedures, we are confident that Kepler, in two-gyro mode (K2G), can achieve similarly excellent results in certain parts of the sky as those Kepler has achieved to date. We thus expect that a K2G/KES can produce many dozens of gorgeous SN lightcurves with similar detail and sensitivity as those we have derived from out GO data. We show an example of a likely SN of Type IIp in Figure 4. This light curve shows the very high quality of the data (1 part per thousand), even at 18th magnitude. The bottom panel also shows a clear change in slope, which has never been seen before in early SN light curves. Light curves of Type Ia SNe candidates are shown in Figures 1 and 2.

Our proposed science depends only slightly on the ability to observe particular locations in the sky: the objects we propose to observe (small galaxies) are more or less uniformly distributed over the sky, and we were able to identify 10-20k galaxies even at the low Galactic latitudes of the Kepler Field. The new and exciting science that K2G can deliver does depend on Kepler's ability to simultaneously provide the four unique capabilities mentioned in the Introduction. However, the long dwell times (#3) *need not* be achieved at the same position or in an uninterrupted fashion: as long as the same total time can be obtained, the science return will be similar. Spreading these observations over a number of observing seasons and/or a number of different celestial positions affects the efficiency of the program slightly.

NASA's recent *"Call for White Papers: Soliciting Community Input for Alternate Science Investigations for the Kepler Spacecraft"* and the subsequent pointing performance study describe a mode of operation in which only two of Kepler's gyroscopes are functional. It is our understanding that these documents imply that a Kepler-like observing strategy can be achieved, without a significant rewrite of the on-board software, provided that the spacecraft (S/C) points in a limited range of positions. For this white paper, we assume that a Kepler-like observing mode can be achieved in the so-called "+velocity direction" (+V) in the Ecliptic plane, where the Sun remains in the XY plane, and in the direction of orbital motion, except that the total dwell time per target area is reduced from the Kepler case. We also assume that the S/C can dwell on targets for about two months while staying safely within requirements for solar angles. As a result, the S/C's roll around the telescope boresight would be small enough to employ the standard Kepler observing strategy. For long time scale photometric stability our reduction software sums counts over 25 or more pixels, therefore a drift across a pixel or even two would not significantly affect the precision. We also model out the affects of nearby stars known from ground based images and/or a summation of all Kepler data.

Extragalactic Science Goals

Kepler offers a unique opportunity to observe the early light curves of supernovae in unprecedented detail. No other experiment— past, present, or presently planned— provides the continuous monitoring throughout the critical first few days of an SN event because none are continually monitoring at 30 minute intervals. This program is sensitive to shock breakouts in core collapse supernovae which could constrain the physics of the early explosion and stellar evolution. For AGN, Kepler science can include studies of AGN in a quieter phase than previous studies and better determine the true rate of AGN activity. With short timescale monitoring of AGN, one studies close to the blackhole event horizon and can even detect stellar tidal disruption events where a star falls into a blackhole.

The Kepler extra-galactic mission would be done with coordinated ground-based observations of the field. Photometric monitoring of the same galaxies on a daily or weekly cadence would quickly alert us of transients in the field even before the Kepler data is downlinked. Team members have a long history of obtaining and utilizing spectroscopic resources for the rapid classification and follow-up of transient sources.

A Kepler extra-galactic mission might attract cooperation with current ground-based transient searches such as KAIT, Pan-STARRS, DES, or PTF. Regardless, our team will also be fielding the ATLAS "Prototype Telescope" that will nightly monitor the Kepler ~100 square degrees for transients with a sensitivity of 5-sigma at m=19.

Spectroscopic classification of the large number of galaxies in the KES field does not require the time urgency of the supernova science and can leverage the multiplexing spectroscopic capabilities on large field-of-view facilities, such as AAOmega. A campaign on such a facility can occur during, and prior to, the KES, and will provide a robust spectroscopic resource to the photometric data obtained, complimenting our science goals but also a value-added resource to the archival data.

Extra-Galactic Science with Kepler

Supernovae

The progenitors of Type Ia supernovae remain a mystery despite their importance as fundamental distance indicators. We still do not know if Type Ia explosions come from binaries made of one or two white dwarfs. Recent models show that the secondary star in a single degenerate binary will cause bright shock emission in the first hours or days after the explosion, while double degenerate explosions are expected to brighten monotonically.

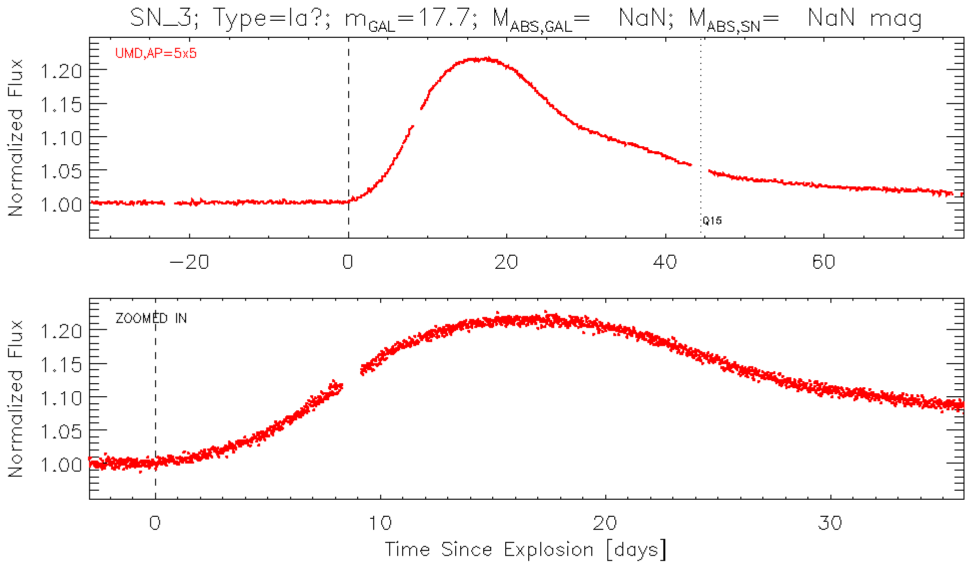


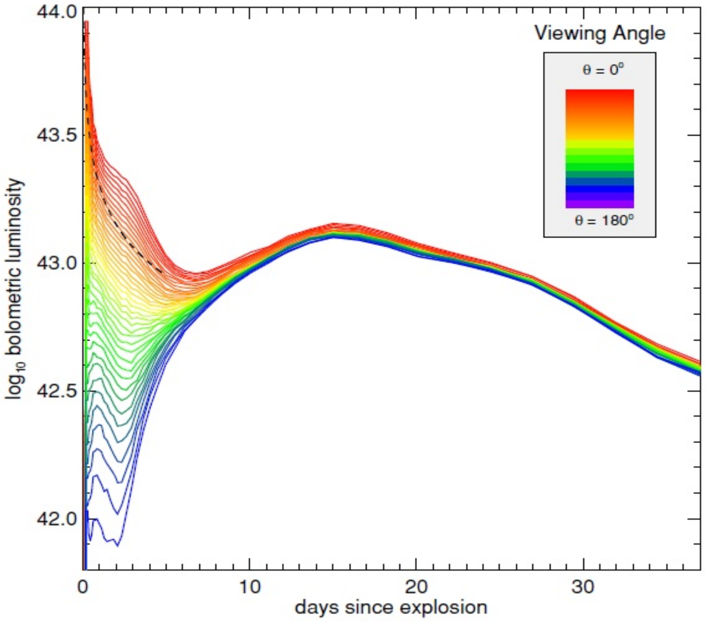
Figure 2: Another transient that we photometrically classify as a Type Ia supernova. Like our SN_2 in figure 1 above, this SN candidate does not show significant features in the early lightcurve, and a hump around t=35 days.

Specifically, the 30-min cadence of Kepler observations can provide the best rise-time information ever obtained for a thermonuclear supernova and tightly constrain the shock breakout of a core collapse event. No current or planned supernova search will have the cadence and continuous coverage of the Kepler mission which is essential for the detection and study of the first hours after a supernova explosion. We can look for long term features in transient and supernovae explosions, looking for clues to the explosions mechanisms in these celestial explosions. Finally, the 30-min cadence will give us unprecedented detail of the activity of black holes in the centers of galaxies.

Supernova Rising

The traditional long cadence of past supernova searches has guaranteed that most supernovae were found at or past maximum light. Yet there is clearly a tremendous amount of information about the explosion contained in the early phases of the light curve.

The SDSS-II supernova search repeatedly visited the same patch of sky as often as once every-other night and it has provided the best constraints yet on the early light curves of Type Ia explosions (Hayden et al. 2010). But even with this intended cadence, the combination of weather and interference from the Moon resulted in an actual average time between visits of more than four days, leaving large gaps in the early rise-time light curve. Other surveys, such as PTF and Pan-STARRS continue moderate cadence searches. Fortuitously, the nearby supernova 2011fe in M101 was observed less than a day after its explosion and this led to serious constraints on the size of the progenitor (Bloom et al. 2012).



Model light curves of a type Ia supernova from a single-degenerate progenitor with a giant star secondary (Kasen 2010). The ejecta shocked by the secondary adds to the supernova light for the first five days or less. The shock is best seen at angles close to the line between the two stars, but it can be detected at nearly all viewing angles. The typical type Ia peaks at MV = −19.3, or at m = 17 mag at z = 0.05. So with Kepler we would easily detect the shock emission more than a factor of 10 fainter than the peak of the supernova.

The Physics of Type Ia Light Curves:

Type Ia supernovae are bright because they synthesize about half a solar mass of radioactive ^{56}Ni which heats the expanding ejecta. Empirical studies show that the yield of radioactive elements directly correlates with the brightness decline rate after maximum (Phillips 1993). This is what makes Type Ia supernovae such good distance indicators. Until recently it was assumed that the variation in rise-time (the number of days between explosion and peak luminosity) followed the decline rate and there was a one-parameter family of light curves described by a single “stretch” parameter that multiplies the time axis. Strovink (2007), using a small sample of nearby supernovae, and Hayden et al. (2010a) using the 300 supernovae in the SDSS-II sample, found that the rise-time is not strictly correlated with the decline rate and that the typical rise-time is only 17 days long instead of the 20 days found in previous studies. The independence between rise and fall times suggests that a second parameter, beyond the nickel yield, is at work. This unknown variable may be the kinetic energy of the explosion, the metallicity of the progenitor, or the degree of mixing of radioactive elements in the ejecta (Woosley et al. 2007).

Arnett (1982) analytically showed that just after the explosion the radioactive energy deposition exceeded the luminosity losses and the supernova should brighten at a nearly constant temperature. He predicted that the flux should rise as the square of the time after explosion (t^2). The SDSS-II supernova survey finds rough agreement with the t^2 prediction (see Figure s1 and 2), but not with the expectation of constant temperature. This is a puzzle since variations in temperature should dominate the flux. The SDSS-II light curve was constructed by combining many light curves to fill in gaps in the early light curve. Kepler can provide well-sampled individual light curves to check the t^2 prediction.

Just Shocking!:

If Type Ia supernovae result from accretion onto a white dwarf from a non-degenerate star, then there should be some observational evidence of that star. Kasen (2010) has calculated detailed models of the collision between the supernova ejecta and the donating star and predicts that shock emission will be visible, but the amplitude depends on the size of the secondary, the binary separation and the viewing angle. The presence of the shock is a great test between the single degenerate progenitor model and the double degenerate merger scenario (Figure 3).

Hayden et al. (2010b) analyzed 100 well-sampled light curves from the SDSS-II rolling supernova search in an attempt to find evidence for shock emission. No clear shock signature was found, but simulations show that, even with the good cadence of SDSS-II, only giant star companions could be ruled out. According to Kasen's models, main-sequence companions produce fast-fading shocks that are significantly fainter than the peak luminosity of the supernova. Because of the short duration of the shock and the viewing angle dependence no stronger conclusion on the type of progenitor could be made from the SDSS-II data. A better experiment with a rapid cadence is needed for the shock test to be conclusive.

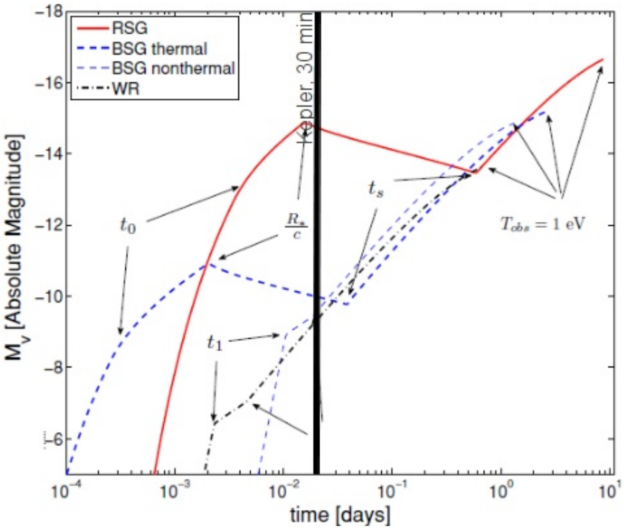


Figure 3: Model light curves of core collapse supernova shock breakouts based on non-thermal equilibrium calculations of Nakar & Sari (2010). The red line shows the optical light curve expected for a red supergiant progenitor. The RSG shows an early peak and then a decline or plateau before rising again a day after the explosion. The blue supergiant and Wolf-Rayet stars are more compact than RSG and do not show an early peak. Kepler's time resolution (30 min) is indicated by the thick vertical line.

Shock Breakouts in Core Collapse Supernovae:

Core collapse supernovae detected will provide similarly exciting insights into the explosion mechanism, based on unique early time light curve information. The shock generated by the creation of a neutron star propagates to the surface and breaks out with a temperature of several million degrees. Details of the shock break out have been hinted at with fortuitous discoveries of SN 2006aj and 2008D (Modjaz et al. 2009;

Soderberg et al. 2008) and these discoveries have generated a new interest in shock breakout modeling.

The observational aspects of the shock breakout depend strongly on the evolutionary status of the massive star at the time of core collapse. For example, Nakar & Sari (2010) predict that shock breakout in an exploding red supergiant will have an early peak in optical flux, just an hour after shock breakout (figure 4). In contrast, more compact blue supergiants (like SN 1987A) and Wolf-Rayet progenitors should not show an initial peak.

Exotic and Fast Transients:

In addition to "classical" supernovae, this program will be sensitive to several other classes of variable or transient objects. In Fig. 5, we present the light-curve of one such object found in the Kepler survey.

Previous surveys are optimized for bright, slowly evolving supernovae, so most are insensitive to exotic events that probe the physics at the boundaries of supernova progenitor populations. Failed supernovae (e.g., Fryer et al 2009) are explosions that do not (quite) undergo a classic supernova explosion: (i) accretion-induced collapse from a white dwarf to a neutron star, where the nuclear burning that powers a Ia supernova is quenched by neutrino cooling; (ii) fallback supernovae, where much of the ^{56}Ni that powers a Type II supernova light curve falls back onto the nascent neutron star; and (iii) "0.Ia" supernovae, where helium accreted onto a white dwarf can burn explosively. Rate predictions for these explosions are highly uncertain at present. Continuous monitoring with Kepler could provide the first clear observations of such explosions. Such observations have potential to constrain the lowest mass supernova progenitors, the transition between black hole and neutron star formation, and behavior in white dwarf binaries with potential to become SNIa.

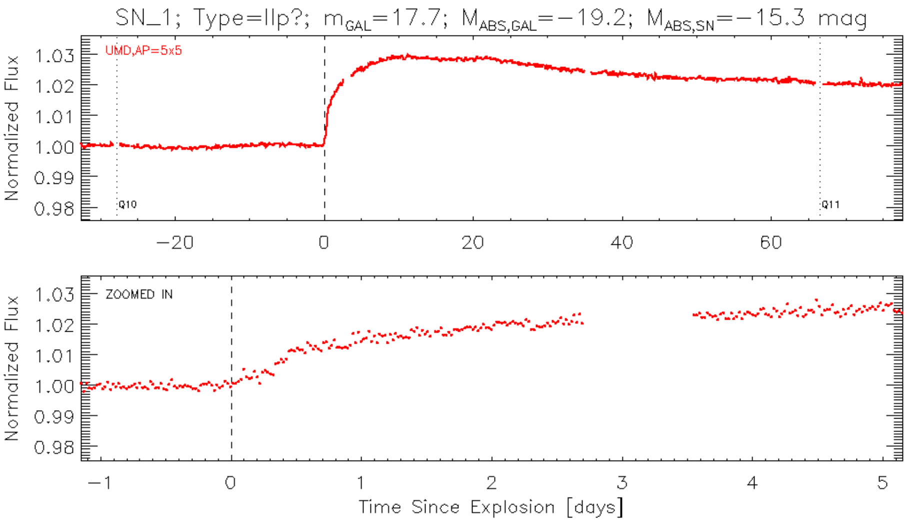


Figure 4: The first SN candidate found in our GO program (Olling et al, 2013, in preparation). This SN shows a very quick rise, to 1/2 of maximum in about 20 hours, and achieved a peak luminosity of ~3% of the host galaxy after 10 days. A clear change in slope is visible in the bottom panel at 0.6 days. The light curve in the top panel is smoothed on a timescale of 1/3 day. The bottom panel shows the individual data points. This light curve is derived with our own specialized software that achieves long-term photometric stability. The gap between 2.7 and 3.5 days is a downlink period.

Active Galactic Nuclei

Galaxies are expected to have super-massive blackholes at their centers, with blackhole mass proportional to bulge mass. Moreover, a significant fraction, 40% of them show spectroscopic signatures of accretion onto black holes (Ho, Filippenko & Sargent 1997). With this program we will be able to measure variability of nuclear blackholes with unprecedented time sampling and sensitivity for a large, unbiased sample of galaxies. Such data will have great legacy value for constraining models of massive black hole formation and accretion onto SMBHs in the centers of galaxies.

Several mechanisms have been proposed to explain AGN variability, but none are entirely satisfactory in fitting the details of observations. The optical variability that Kepler explores is probably related to accretion disk instabilities, variation in accretion rate or changes in the accretion disk's structure. Statistical analysis of the light curves from thousands of AGN would reveal the physical character of the parcels of gas and dust eclipsing or falling into AGN and allow better models to be developed of the inner accretion disks/tori. Variability may be a proxy for size. X-ray data suggest that the emission region size actually increases towards lower luminosity for the weakest AGN (Ptak et al 1998). A corresponding optical measurement will test for similar behavior at lower temperatures. Again, the study is enabled by Kepler's unique cadence and photometric accuracy.

New, Low Variability, AGN with Kepler

The light curves of AGN are often characterized by variability on many time scales. In fact, variability in surveys is an easy and reliable way to identify AGN. Since the amplitude of variability increases with time scale, it becomes easier to identify AGN if one samples over longer time frames. For example, Wilhite et al (2008) find, from SDSS stripe 82 data, a variability of ~0.05 (0.1) [0.2] mag at time scales of 10 (30) [200] days for their group of lowest luminosity AGN. The light curves of AGN are often characterized by variability on many time scales. In fact, variability in surveys is an easy and reliable way to identify AGN. Since the amplitude of variability increases with time scale, it becomes easier to identify AGN if one samples over longer time frames. For example, Wilhite et al (2008) find, from SDSS stripe 82 data, a variability of ~0.05 (0.1) [0.2] mag at time scales of 10 (30) [200] days for their group of lowest luminosity AGN. Thus the long timescale, high precision of this survey will detect AGN at unprecedented low variability levels.

We expect that a majority of the AGN event horizons will be larger than a day and therefore the amplitudes of variation will be quite low time scales much under a day. Nevertheless, on these timescales Kepler will give us for brighter sources better than mmag sensitivity to variations. At this level one is no longer looking at overall changes in the AGN's brightness, but rather even smaller event zones. This could be hotspots in the accretion disk, or activity at the base of the jet. Whenever we take spectra of these objects, we will also have the short timescale history occurring at the same time from Kepler (although downlinked some time later).

Stellar Tidal Disruptions

Other, rarer events such as tidal shredding of stars by BHs near the nucleus could also cause sudden brightening there. Magorrian & Tremaine (1999) predict event rates for tidal shredding of up to 10^{-4} per galaxy/yr and peak luminosities that may rival a SN. The duration of such events may be as short as 10 days (Strubbe & Quataert 2009). Several such events have been found in GALEX and ROSAT data (e.g., Gezari et al. 2009, 2012). These stellar disruption events have a distinct behavior for variability as a function of time allowing their identification. We might expect to observe a few of those events in a

KES program.

Data Analysis and Other Considerations

We have developed a procedure to obtain accurate photometry from Kepler even over months for the centers of galaxies where AGN lie. Our target galaxies are chosen to be so small (in projection) that they extend just a few Kepler pixels in size. The KES galaxies will be similarly small, and will be selected using a procedure that uses 2MASS, WISE and USNO-B photometry (Olling et al, 2013b).

Our procedure to generate light curves is quite different from that which the Kepler project performs for planetary science because there the important time-scale is short: minutes to hours. On longer times the centroids of objects move significantly within a pixel, often crossing a pixel boundary, and also the PSF slowly changes. However, we have found that by using large aperture photometry, generally around 5x5 pixels or larger, and carefully subtracting fits for neighboring stars, that we can obtain excellent long term stability of the calibration. We also make use of the FFI's to see monthly trends in the focus, PSF, and sensitivity. We use catalog data at higher resolution to give details of the stars in the neighboring pixels, and we use the sum of the target stamps over a quarter or year to detect extremely faint nearby stars. If the drifts over 30 minutes in K2G are of order a pixel or two, as is expected for fields in the ecliptic, then the stability of our procedure should be unaffected.

The photometry is improved if we have many sky-only pixels within the stamp and our source detection efficiency improves with the size of the stamp. However, the number of targets decreases if the target stamp is too large. A best compromise is probably around 12 x 12 pixels, but that number depends on Kepler observatory factors that are as of yet unknown.

There are a number of ways in which modification of the Kepler software would benefit the KES program. But note that *no changes are required* given the information currently available to us. For example, the KES galaxies will all be rather faint, and the dynamic range of the data will be much smaller than the requirements for Kepler's primary mission. Thus, many fewer bits are required for the KES galaxies, which would free up downlaod capacity for other targets in the KES fields. If significant trailing *would* occur in K2G mode, then it would be important to make sure that Kepler's cosmic-ray rejection algorithm would not reject the trailing sources. Finally, an on-board transit detection algorithm would open up the Kepler mission to the unknown unknowns (transits outside cataloged stars and galaxies), and would also decrease the pressure on our ground-based programs.

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