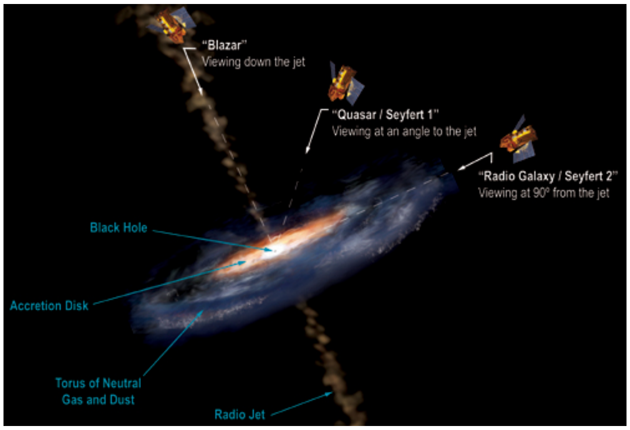
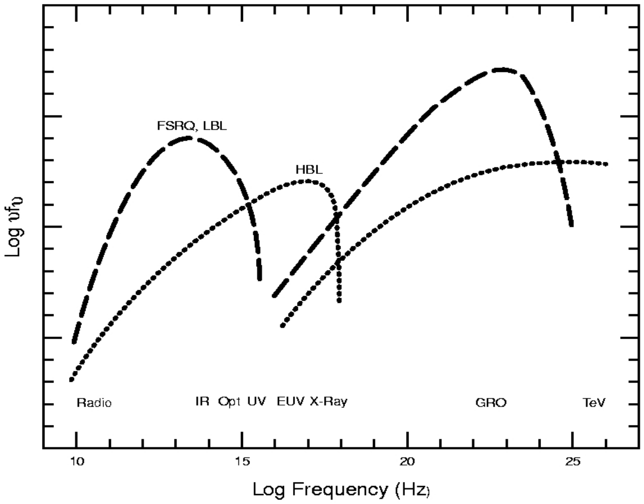
A proposed 2-wheel operation scenario and alternative science investigations for the Kepler spacecraft.

Submitted by Dr. Michael Carini, Department of Physics and Astronomy, Western Kentucky University

Abstract: A two-wheel operation scenario for the Kepler spacecraft is proposed, with blazar astrophysics as a primary science driver. In addition to blazar astrophysics, this scenario will enable a wide variety of other astrophysics to continue to be accomplished with the Kepler spacecraft. The operations scenario is comprised of two elements: a monitoring element and a target of opportunity element. In the monitoring element, the spacecraft cycles through multiple fields providing high precision, regularly sampled light curves of blazars. In the target of opportunity element the spacecraft responds to flaring blazars providing high time resolution, high precision photometry of blazars during flaring events. Studies of blazars are aligned with the 2010 NASA science plan for astrophysics.

Scientific Motivation:





The accepted model of the active galactic nucleus (AGN) phenomena starts with a central, supermassive black hole (SMBH) with a mass ranging from 10^6-10^9 $M_\odot$. Surrounding the SMBH is an accretion disk with radius on the order of 100 AU, which broadens to a dusty molecular torus at its outer edges. Clouds of gas, which comprise the broad line region when they are close (several light days to several light months) to the central SMBH and the narrow line region when they are found at larger distances from the central SMBH, exist above and below the disk and are illuminated by the accretion disk. Perpendicular to the accretion disk are two jets composed of energetic particles that are moving away from the central SMBH at relativistic velocities. The type of AGN we observe depends on the angle the jet makes with the line of sight and the strength of the jet itself. In the case of the blazars, we are looking straight down the mouth of the jet, and the radiation is being beamed directly at us. Thus, we see an object that is an extreme example of the AGN phenomena, and which provides a laboratory to test models of relativistic jet physics.

The defining characteristics of blazars are a featureless (or nearly featureless) optical continuum, large amplitude and highly variable polarization, and large amplitude continuum variability at all wavelengths. The dearth and in some cases absence of discrete features in their spectrum leaves us with only continuum variability as a diagnostic of the emission mechanisms at work in these objects. The blazar class of objects is comprised of the BL Lacertae (BL Lac) objects and the flat spectrum radio quasars (FSRQ). The difference between a BL Lac and a FSRQ quasar lies primarily in the strength of any emission lines present. In the BL Lac objects, emission lines are non–existent or are present with equivalent widths < 5 Å, while in the FSRQ emission lines are present with equivalent widths > 5 Å. Blazar spectral energy distributions (SEDs) display a two-bump structure as shown the figure above (Urry 1998). At low energies (radio-soft x-rays), there is a peak arising from synchrotron emission in the jet, while at higher energies (hard x-rays-TeV) the peak is believed to be the result of inverse Compton scattering of photons. The origin of these photons, the so-called seed photons, is one of the most important questions in blazar astrophysics. The location of the low energy (synchrotron) peak divides blazars into sub-classes. In the low frequency peaked BL Lac objects (LBL) and the FSRQ, the synchrotron component peaks in the IR-optical regime, while in the high frequency peaked BL Lac objects (HBL) the synchrotron peak is in the UV to soft/hard x-ray regime. The inverse Compton component peaks at gamma ray wavelengths for LBLs and FSRQs and TeV energies for the HBLs. Despite decades of observations, many open questions remain concerning both the character of the continuum variability (timescales, wavelength dependencies, interpretation) which relates directly to our fundamental understanding of blazars, and the physical mechanisms at work which produce the observed two hump spectral energy distribution and its temporal behavior.

A fundamental question in blazar astrophysics is what is the mechanism (or mechanisms) producing the observed variability and the two hump nature of the SED. There are two broad classes of models that can explain the structure observed in the spectral energy distributions of blazars: leptonic and hadronic models. The leptonic models are highly favored and most often invoked to explain blazars. The key to testing and distinguishing between the various leptonic models of the SED lay in multi-wavelength monitoring. It is well understood that the low energy peak is produced by synchrotron emission arising from electrons in the relativistic jet. However, the origin of the second peak, i.e. the gamma ray - TeV peak, is less well constrained. There are two competing leptonic models which explain the high energy flux observed in these objects; both have as their basis inverse Compton scattering of photons. In the synchrotron self-Compton model (SSC, Bloom & Marscher 1996), the seed photons are created via synchrotron emission in the jet and scatter off the same population of electrons that produced them. In the external radiation Compton models (ERC), the seed photons are produced by emission line clouds (Sikora, Begelman and Rees 1994), the accretion disk (Dermer & Schlickeiser 1993), or a molecular torus (Blazejowski et al. 2000). A variation on the ERC models are the mirror Compton models where the seed photons are created within the jet, and are scattered off broad line region clouds and then back into the jet (Ghisellini and Madau

1996). They are then scattered by the relativistic electrons within the jet, producing the high-energy emission. A direct test of these models is the construction of light curves and the search for lags between simultaneous optical and gamma ray light curves, since the prediction is that the optical outbursts may lead or be simultaneous with the gamma-ray outbursts (Sikora, Begelman and Rees 1994). Sokolov, Marscher and McHardy (2004) and Sokolov and Marscher (2005) define the expected lags between low and high energies and spectral behavior for SSC and ERC models in the context of the shock in jet models. In the SSC model, no lag will be observed if the decay time for the synchrotron and inverse Compton emission is less than the crossing time. When the decay time becomes on the order of or larger than the crossing time, then the inverse Compton flare will lead the synchrotron (optical) flare. If, however, one compares the synchrotron emission at the high frequencies (optical) of the synchrotron emission to the inverse Compton at low inverse Compton emission frequencies (soft x-rays), the x-rays will lag the optical. This is not expected from ERC models, and immediately discriminates between and SSC and ERC process. In the ERC models, the synchrotron flare leads the higher energy flare. In order to differentiate between this and the SSC case that shows a similar lag, one needs to investigate the spectral index of the inverse Compton emission. The spectral index of an SSC flare will be negative throughout the duration of the flare, while for a high-energy flare cased by an ERC process, the spectral index will be positive for at least half the flare. Sikora et al. (2001) show that if the ERC induced high energy flare lags the synchrotron flare by a significant (1 day or greater) delay, then mirror Compton models apply.

Both process, SSC and ERC, have been shown to be at work in blazars. SSC models have been used to successfully explain the multi-wavelength observations of S5 0716+714 (Foschini et al. 2006), MKN 501 (Gliozzi et al. 2006), 1ES 1959+650 (Gutierrez et al. 2006), and MKN 421 (Rebillot et al. 2006). Mukherjee et al. (1999) determined both processes to be at work in PKS 0528+134. Ghisellini et al. (1998) and Taveecchio et al. (2002) model the SED of 3C 454.3 with an ERC model. Fan, Cao, & Gu (2006) successfully applied ERC models to 40 objects and Ghisellini et al. (1998) found satisfactory fits to the SEDs of 51 objects from both the ERC and SSC models. Ghisellini et al. only fit the SEDs; they made no tests of lags between flares at different wavebands. Overall, it appears that the SSC process dominates in the TeV Blazars (HBLs), while ERC process dominates the LBLs. However, we do not know if/why a given source may favor the SSC process while another favors ERC processes, nor do we know if and/or why both processes may be at work in a given object. Determining which process or processes are at work in a sample of objects and then correlating that with other known parameters will provide a clear picture of the emission process at work in these objects. With the ongoing operations of FERMI, the continued monitoring of blazars at TeV energies by the VERITAS array, this goal is attainable, provided the appropriate optical coverage can be obtained, which is possible in our proposed operational scenario for a two wheel Kepler mission.

It is important to stress that a single campaign of multi-wavelength monitoring can lead one to erroneous conclusions, since the source behavior can change from campaign to campaign. An example of this is the behavior of PKS 2155-304 in 4 different campaigns of multi-wavelength monitoring (Urry 1999). PKS 2155-304 showed different mutli-wavelength behavior between the four campaigns, illustrating the danger of relying on one campaign of multi-wavelength observations as well as the dangers of extrapolating the results from one blazar to all blazars. Another example of this is the TeV source 1ES 1959+650. In 2002, 1ES 1959+650 underwent a correlated TeV and X Ray flare that was well fit by SSC Models (Krawczynski et al. 2004), although unlike the TeV source PKS 2155-304, there was no correlation between the optical flux variations and the higher energy variability. However, 20 days after the main flare, a secondary X-ray flare occurred, with no corresponding TeV flare and a correlated, but low amplitude optical flare. This is not consistent with the predictions of the SSC model, but has been well explained via hadronic mirror models (Bottcher, 2005). The lack of a correlation between the optical and TeV is reconcilable with SSC models if the TeV and optical emission are not produced in the same location, though this has serious implications for the common practice of using optical monitoring to trigger TeV observations of flaring behavior. Confirming (or not) through further multi-wavelength campaigns that this lack of correlation is ubiquitous to TeV blazers is an important test of this assumption. Thus, we must observe and observe a lot across the electromagnetic spectrum in order to fully understand the behavior of these sources.

Finally, consider the case of 3C 454.3. As mentioned above, Ghisellini et al. (1998) and Taveecchio et al. (2002) model the SED of 3C 454.3 as observed by EGRET in the early 1990’s, when it was at a low optical flux state, with an ERC model. Katarzynski & Ghisellini (2006) point out that if the same model is applied to the historic 2005 outburst (Fuhrmann et al. 2006), a high-energy flare should have also occurred (though there are no observations available to confirm this) and the jet would have changed its total power by a large factor. They propose a more “economical solution”, whereby it is possible for the jet to work at a constant power, but produce blobs with different speeds and thus different Lorentz factors. In this scenario, one envisions that the blob that produced the 2005 outburst had a small Lorentz factor, and thus much lower inverse Compton contribution. In this case no corresponding high-energy flare would have been seen. This model is testable with simultaneous optical-gamma-ray observations of flares in this and other blazars.

These three examples clear demonstrate the need for continued study of these sources at different epochs and at different activity levels, since there is mounting evidence that there is no one emission mechanism at work. Single epoch campaigns that do not provide data capable of fully describing the time evolution of the flux at multiple wavebands are not sufficient to confront emission models and can lead to erroneous conclusions concerning the nature of the emission process in these sources. Although the question of whether or not the optical variability is correlated with the TeV is unanswered, enhanced optical activity does appear to be a signature of enhanced synchrotron activity that is generally closely correlated with enhanced TeV particle acceleration (Ravisio et al. 2002, 2003). Thus a TeV flare does indicate that one should expect enhanced optical activity. Chatterjee et al. (2012) showed that for their sample of six blazars, the gamma ray (FERMI) and optical variability properties were very similar, indicating that increased gamma ray flux indicates increased optical activity in these sources. Better sample data and a larger sample of objects could dramatically improve upon their results.

Another important question in blazar astrophysics is the origin of the observed flares seen across the electromagnetic spectrum. The overall light curve structure of blazars at all wavelengths is interpreted as a steady baseline flux on which there exists a superposition of flares arising in the jet and/or accretion disk. Well-sampled, simultaneous optical-gamma ray light curves of flares provide information on the origin of such flares. This is accomplished via a flare decomposition methodology (Valtajoa et al. 1999). Once decomposed, the flare rise and decay times are then inspected to determine if they are symmetric (indicating the radiative cooling time of the electrons generating the synchrotron and inverse Compton emission is smaller than the time needed to inject the particles into the region responsible for the emission) or asymmetric, with a fast rise time and long decay time (indicating that the radiative cooling timescale is longer than the injection timescale). Chatterjee et al. (2012) successfully applied this to a sample of six blazars finding only symmetric flares. This result was consistent with a disturbance in the jet moving through a standing shock. However, their analysis had to account for seasonal gaps and the data had to be smoothed to match the Fermi sampling. Such pre-analysis massaging of the data can induce unintended effects and can be avoided with our proposed Kepler operations scenario.

Results from the WISE observatory have produced a wealth of new blazar candidates across the sky. Massaro et al. (2011) found that blazars inhabit what they call the WISE blazar strip. This is a narrow strip in the [3.4]-[4.6]-[12] μm WISE color-color diagram where blazars are preferentially located compared to other AGN types. D'Aubrusco et al. (2012) found that gamma ray emitting blazars inhabit a narrow subregion of the blazar strip they call the WISE Gamma-ray strip. Optical magnitudes can be determined for these sources from catalogues such as the Naval Observatory's Nomad catalogue or ground based photometric efforts. High precision, well-sampled light curves provide additional evidence of the blazar nature of these sources, as the typical blazar variability is aperiodic and has large amplitude compared to other classes of AGN. The sampling and photometric quality of the Kepler observations would identify the sources as blazar candidates much quicker than ground based observations would be able to accomplish. It may take several observing seasons of ground based observations to have a light curve of sufficient quality to identify the source as a likely blazar; one year of Kepler observations will be sufficient for this task. This would then provide more direction as to sources to include in spectroscopic observations that provide a firm source classification. In addition, the Fermi catalogues (including the unassociated source catalogues) would be searched to see if the sources identified based on their optical variability are consistent with known gamma ray emitting sources.

Although much progress has been made, this has been in spite of rather poor optical coverage and light curves (except in specific cases), not because of it. More often than not, multi-wavelength studies that address the questions outlined above have been accomplished with fair to poor optical sampling. Well sampled, long term light curves are difficult to obtain from ground-based facilities. Any single facility suffers from a number of limitations that prevent routine sampling of blazars; most important among them are other scientific priorities, weather, the diurnal cycle and the fact that at certain times of year sources are too close to the sun to be observed from ground based observatories. Use of multiple ground-based observatories can of course mitigate the effects of weather and if they are strategically placed, the effects of the diurnal cycle. The cost is one of organization, cooperation and management. In addition, such arrangements may work for short, very focused efforts on a single source (eg. the OJ 94 project, Pusimo, et al. 2000) but they are not practical for larger numbers of sources over the long term. An observatory in space can be much less suspect to diurnal cycles and may or may not have a yearly (or other) cycle (depending upon its orbit and other operational constraints) and certainly does not suffer from weather related data gaps. These are the most serious, as they are not predictable or regular in the data. The operations scenario proposed below for Kepler could thus make a significant impact on blazar astrophysics by providing the badly needed, well sampled, high precision optical observations needed to address these open questions in blazar astrophysics. The data gaps that may arise as a result of operational constraints on the Kepler spacecraft will be minimal and predictable.

The *2010 NASA Science Plan for Astrophysics* defines NASA's goal in astrophysics as follows: "Discover how the universe works, explore how the universe began and developed into its present form and search for earth like planets." The science proposed here is designed to understand how blazars and their jets work and clearly fits into this goal for astrophysics. In addition, one of the three science questions that emanate from this goal is stated as " How do matter, energy, space and time behave under the extraordinary diverse conditions the cosmos?" By determining which of the models described above applies to blazars or a particular blazar clearly describes how matter behaves in the extraordinary circumstances found in the blazar relativistic jets. Finally, as these jest are ultimately powered by the supermassive black holes at the centers of blazars, the proposed science addresses the Astrophysics science area objective of "Understand the origin and destiny of the universe, and the nature of black holes, dark energy, dark matter and gravity." Under the proposed operational scenario, additional science that this operations scenario can enable is briefly discussed, all of which fits within NASA goals and objectives for astrophysics.

Operations scenario:

I propose a two-wheel operations scenario for the Kepler spacecraft that involves two key elements. The first element is monitoring on a two-day cycle of observations of a sample of blazars who are optically bright and display VHE gamma ray emission. These observations will provide high precision, uniformly sampled optical time series over several years to compare with Fermi gamma ray and VERITAS TeV light curves to accomplish the science goals described above. Kepler's large field of view will enable opportunities for other science investigations for which this sampling rate is adequate to achieve the science goals. The second element is a target of opportunity element makes use of Kepler's ability to provide high precision, high time resolution observations. This element applies not only to the blazar science described above, but is applicable to any form of transient astrophysical phenomena (nova, supernova, GRB, etc).

In the first element, a sample of optically bright ($m_{kep} < 16$) blazars that are known VHE blazars will be selected for monitoring. In addition to these sources, the current Kepler field of view will be included. The current Kepler field is retained because it has a number of blazars already under study, including the newly discovered blazar W2R 1926+42 (Edelson et al. 2013) and a number of identified blazar candidates (Carini 2013 in prep). In addition, it contains one of the most optically active Seyfert 1 galaxies known: ZW 229+015 (Edelson, et al. 2011, Carini & Ryle 2012). The target blazars will be identified taking into consideration the pointing restrictions described in the call for white papers. It is assumed that the time between targets would be equivalent to the time quoted for the momentum reset and the longest time quoted of 1 hour has been used in the calculation. If a thirty minute integration will achieve the desired photometric precision (1% or less is ideal, but even 3-5% would be acceptable), then approximately 30 targets can be observed with two day sampling. This results in an estimate of 30 different fields can be observed with 30 minute integration and provide sampling of any individual target with a sampling rate of 2 days. Assuming a nominal drift rate of 1 pixel in 5 minutes, each 30 minute long observation would move the source over approximately 6 pixels. This will require the specification of larger photometric apertures and likely require additional work on data reduction and analysis in order to extract source light curves. It is hoped that project resources would be available to provide at least a uniform method for light curve extraction.

If one assumes that a one minute integration will meet the desired photometric performance, then the total number of possible target fields increases to approximately 45. The advantage here is that based upon the call for white papers, in one minute the spacecraft drift is much less than one pixel. This suggests that the current processing and analysis software tools and techniques would be applicable to the data, and little or no additional effort at analysis would be required at the level of the project or even the astrophysics community. Until the exact nature of the pointing stability and photometric precision are determined, all that can be provided for evaluation are these two scenarios.

In addition to the long term monitoring of the known sources, this element enables opportunities for discovery of new blazars. Using the techniques described above in the scientific justification, blazar candidates will be identified in each target field and selected for photometric monitoring with Kepler. This will open up opportunities for follow on spectroscopic observations to determine the blazar (or other AGN) nature of the sources. In addition, observations with Fermi and other operating missions as well as archival searches for data on these sources would be enabled by these Kepler observations.

This scenario enables a wealth of scientific investigations outside of blazar astrophysics. Given Kepler's large field of view, countless other astrophyscially interesting objects can and will be identified by the astronomical community for photometric studies with the proposed sampling rate. Studies of binary star systems, intrinsic stellar variability, supernova, nova, cataclysmic variable stars, gamma ray bursts are but a few of the other fields of astrophysics which would clearly benefit from observations obtained in this scenario.

Under this element, keeping the number of possible targets within the current Kepler limit of 170,000 and operating on a quarterly system of data downloads implies that the data storage requirements would be consistent with Kepler's current capabilities and in line with the current operations scenario. There is no compelling scientific reason for data downloads more frequently than every three months for this element of the operations scenario.

It is worth noting that the science described can be achieved via a number of permutations to this operational scenario. If the described cycling between different attitudes is not attainable because of momentum management constraints, the time at a given attitude and thus the number of sources can be changed. The final number of sources would be limited by a desire to be able to return to the same source once every four days. This matches the four day sampling pattern typically found for the Fermi light curves of the brighter blazars. In this scenario, while fewer sources would be observed, information on the more rapid variability of the sources is obtained, which is also astrophysically interesting.

Element number two is a target of opportunity element that makes use of Kepler's ability to stare at the same field for a maximum of approximately four days at a time while providing high photometric precision. This element would be triggered for blazars when a source is seen flaring at optical (from ground based monitoring) or at VHE (either a flare seen by Fermi, VERITAS or one of the other TeV observatories (i.e. HESS, Magic)). Specific trigger thresholds will be set at each wavelength based on past observations of flares in the target and other blazars. In a flaring state, both Fermi and VERITAS have been shown to be able to obtain daily and sub daily flux monitoring (Fortson et al., 2012, Saito, et al. 2013). In principle, such optical observations are available from the ground. However, the availability of ground based observatories to dedicate days of continuous monitoring to a single source, the inherent constraints of ground based observations, and the complexities of the weather almost inevitably conspire to make any successful attempts at simultaneous time resolved ground based optical and space based observations rare and the result of luck. Kepler is perfectly suited for this type of blazar target of opportunity observation. It is particularly well matched with Fermi, since both are not limited by the day night cycles and can obtain continuous time series. Four days of continuous optical monitoring during a flaring state would provide an unprecedented set of data available for correlative studies of variability on the fastest observed timescales in blazars, which has never been accomplished before at multiple wavelengths. Since Kepler can be repointed and return to the field of the flaring blazar, even longer monitoring during exceptional flares could be maintained, with only the small 30 minute-1 hour gap in the data due to the repointing process. The driving force here will be similar to that in element 1: the photometric precision of Kepler in two-wheel operations will need to be better understood in order to determine the integration times needed and corresponding challenges to the data analysis.

The number of such TOO observations that might be triggered is very difficult to determine, due to the aperiodic nature of blazar variability. Past history suggests that one can estimate that a few, 2-4 per year, might occur. The number of triggers would depend highly on the flux thresholds chosen to trigger the TOO observations. In addition, the additional costs associated with more frequent target uploads and data downloads associated with this scenario would have to be factored into the number of possible TOOs that could be accomplished by Kepler. Data storage should not be an issue in this scenario; only one target will be being observed and thus only on target aperture would be being read out. This would change would be if it were decided that if a blazar TOO is declared, the community is given a brief window of time to submit targets of astrophysical interest in the blazar field of view that if observed continuously would produce scientifically useful results. Thus additional target apertures would be used, though it is not anticipated there would be an overabundance of such additional requests. Nevertheless, it is an option to maximize the astrophysical impact of Kepler. Furthermore, it is unlikely that the data from the blazar TOO would need to be downloaded immediately after the observation; it could wait until a scheduled data download occurred.

As with element 1, this operations scenario has application beyond the blazar community. TOOs could be triggered for any transient astrophysical phenomena: nova, supernova, GRBs etc. The Kepler mission would have to estimate how many such TOOs would be possible based on financial and other mission constraints. There would also be an impact on the ongoing monitoring science from element 1. These observations would be interrupted for the TOO, inducing gaps in the time series. These gaps are almost trivial when compared to the gaps in the time series obtained from ground-based observations and would have a minimal effect on the science. When the potential scientific again of the TOO observations is weighed against the minimal negative impact on the element 1 observations, it becomes clear that the overall scientific impact from Kepler is enhanced with both of these elements in the two-wheel operations scenario.

The length of this operations scenario should be as long as possible, but realistically if Kepler can continue for another 4 years then the scientific goals will be met. Blazars vary on timescales from minutes to decades, so the Kepler observations would provide detailed and unprecedented information on timescales from tens of minutes to years. Of equal, or perhaps even greater, importance is that Kepler will provide for the first times data in the key optical wavelength regime with sampling rates and quality comparable to that obtained at both lower energy (radio) and higher energies (VHE). This will greatly enhance the validity of any correlative studies between the optical and lower/higher energy variability.

Most blazars are point sources, though there are many that do show a small amount of extended emission due to the galaxy component. The variability in question occurs in the core that presents as a point source, thus the extended emission resulting from the surrounding galaxy results in an increased background. Nevertheless, each proposed source and TOO will have to be evaluated for the nature and amount of the extended emission and that will have to be taken into account in the determination of the photometric aperture used for both the observations and the follow on analysis.

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