A Search for New Exoplanets in the TESS Data using Joint Signal Estimation

Proposal for: 2020 Blue Waters allocation for UIUC

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October 2020

1 Project Abstract

One half of the 2019 Nobel Prize in Physics was awarded for the discovery of the first exoplanet in 1995. Transiting exoplanet detection telescopes and missions such as CoRoT(Léger et al. 2009), Kepler (Borucki et al. 2010), K2 (Howell et al. 2014), and TESS (Ricker et al. 2014) have been crucial to expanding the catalog of known exoplanets and their populations statistics. Exoplanet detection is a data- and compute-intensive process and detection efficiency is limited both by the data processing algorithm and instrument sensitivity. Here we propose to expand on prior work on Blue Waters (Taaki et al 2020) in which we developed a novel joint Bayesian detection framework and demonstrated increased detection efficiency compared to standard detection approaches. Our detection framework uses a complete signal model and jointly estimates systematic instrumental noise and the transit signal, avoiding the distortion of weak exoplanet signals by prior signal processing steps. Our prior work focused on targets from the Kepler dataset. TESS, launched in 2018, follows as the successor to the Kepler mission. In this proposal we request an allocation to perform the first independent large-scale search for undetected exoplanets among the persistent targets in the first year of TESS data using our new algorithm. All codes to perform this research have been developed and tested in the previous allocation. Joint Bayesian estimation is statistically superior but requires petascale computational resources. This proposal represents a unique opportunity for Blue Waters to participate in the discovery of new exoplanets in a recent space mission.

2 Field of Science

The field of science of the proposed project is Astronomical Sciences.

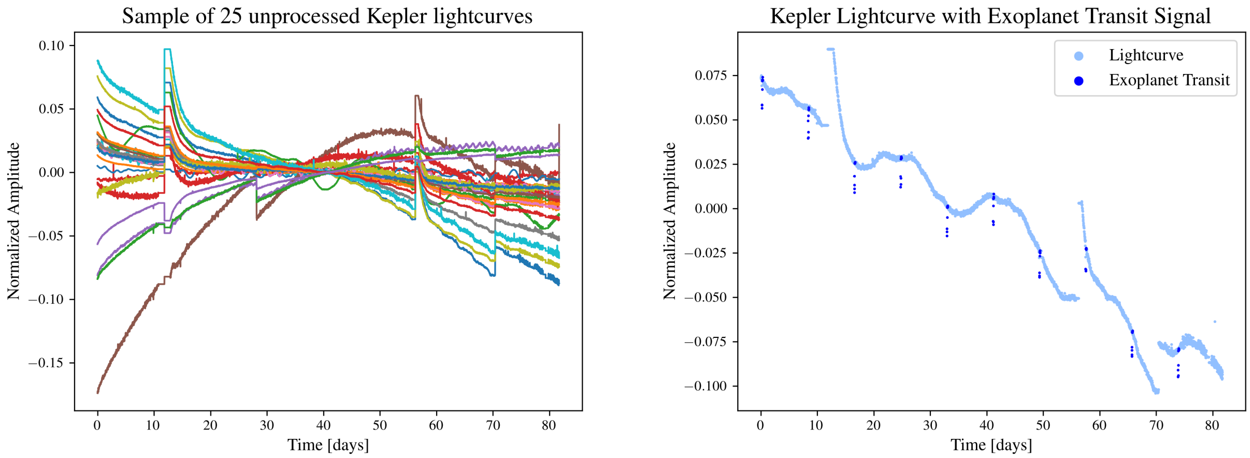
3 Team Members

The research proposed here forms part of the Ph.D. thesis of Jamila Taaki (Co-I). She is advised by Professor Farzad Kamalabadi (ECE) (Co-I) and Professor Athol Kemball (Astronomy) (PI).

4 Project Overview

The 2019 Nobel Prize in Physics was awarded for the first detection of an extrasolar planet (exoplanet) in 1995 (Howell 2020). Since this discovery exoplanet studies have become one of the prime drivers of research in contemporary astrophysics. One of these key contemporary science challenges is to develop an unbiased complete sample of exoplanetary systems, their host stars, planet properties, and planetary orbital configurations. This would aid our understanding of the prevalence of Earth-analog planets, solar system formation, and conditions for life (Deeg and Alonso 2018). As a result, expanded exoplanet searches are a current major focus in the field. **In this proposal our goal is to undertake a novel search for exoplanets, uniquely possible with Blue Waters, in data taken by the Transiting Exoplanet Survey Satellite (TESS) launched in 2018.**

Transit detection is a method to find exoplanets in orbit around a star from time-series brightness measurements (lightcurve) of an unresolved star-planet system. A planet will produce a brief but detectable dip in the observed stellar brightness as it eclipses our line of sight to the star; this is referred to as a transit signal. A transit signal is roughly parameterized by the duration of dimming, the orbital period and the epoch (reference start time). The Kepler space mission was extremely successful in expanding our understanding of the population of exoplanets, detecting over 3500 exoplanets to date (Batalha 2014). The TESS mission is the successor space mission to Kepler (Ricker et al. 2014). Transit instruments produce time-series data (lightcurves) for many thousands of stellar targets. TESS observes 15,000 targets in high cadence (2 minute) mode at any one time and many more in a low cadence (30 minute) mode. Only a very small fraction of targets have a planet aligned by chance so as to be observable in transit; for Earth this probability is less than 1% (Borucki and Summers 1984).



(a) Sample of Unprocessed Lightcurves

(b) Single Lightcurve

Figure 1 (a): A subset of time-series brightness measurements for Kepler targets obtained from the same CCD sensor (for a 90 day window). Noticeably the time-series measurements are dominated by correlated (co-trending) instrumental systematic noise on a variety of timescales; (b): A single sample Kepler lightcurve with a detected transit signal. Datapoints corresponding to a transit event are highlighted in dark blue.

Transit detection of exoplanets presents unique computational and statistical challenges and petascale computing allows fundamentally new approaches for the first time:

- Exoplanet transit telescopes, in common with general astronomical telescope systems, lack sufficiently accurate instrumental data models and noise characterization to allow calibrated measured data to be used for the inference of scientific observables alone (here characterization of transit signals). Instead calibration and scientific inference are often performed in multiple incremental stages, assuming separability of instrumental effects where possible. The Kepler Science Processing Pipeline developed by NASA for the detection of exoplanets (Jenkins et al. 2010) is designed using this approach for efficient analysis of large volumes by several stages of data processing. The final stage of processing is transit detection. In transit detection, each processed star-planet time series is independently searched for candidate transit signals over a range of durations, periods and epochs.
- In practice, multi-stage incremental processing makes necessary assumptions that often lead to an improper treatment of noise. A transit signal is embedded in systematic and statistical noise (Gilliland et al. 2011)

that typically far exceeds the strength of the exoplanet signal (see Figure 1). For example, instrumental and astrophysical noise may have trends over a range of time-scales, which may mimic or mask transit signals, an example of which is shown in Figure 1.

- As noted above, in the Kepler/TESS Science Processing Pipeline, systematic noise is removed empirically in a data-driven manner prior to searching for an exoplanet. In prior work, we have demonstrated that this process can degrade exoplanet detection, and developed a novel Bayesian approach (Taaki, Kamalabadi, and Kemball 2020) that jointly estimates the systematic noise and astrophysical signal. In this earlier work, we evaluated the comparative performance of both detection methods on Blue Waters using standard injection tests on Kepler long cadence (30 minute) data. Joint estimation improved detection rates ($\sim 2\%$) especially for small exoplanets and short orbital periods where correlation between noise and signal is more likely. Thus the method has significant potential to yield new exoplanets in a particularly important part of parameter space.

Here we propose to apply our novel joint detection algorithm to high-cadence (2-min) TESS data to search for weak exoplanet signals that may have been missed in the standard reduction. The Kepler Science Processing Pipeline was used by NASA to analyse TESS high cadence (2 minute) data with little modification. We will focus on 10,000 targets observed completely during the first year of TESS operation[1]. The area of the southern sky observed during the first year is shown in Figure 2. The increased cadence of observations greatly increases the computational requirements and requires Blue Waters as described in further detail below.

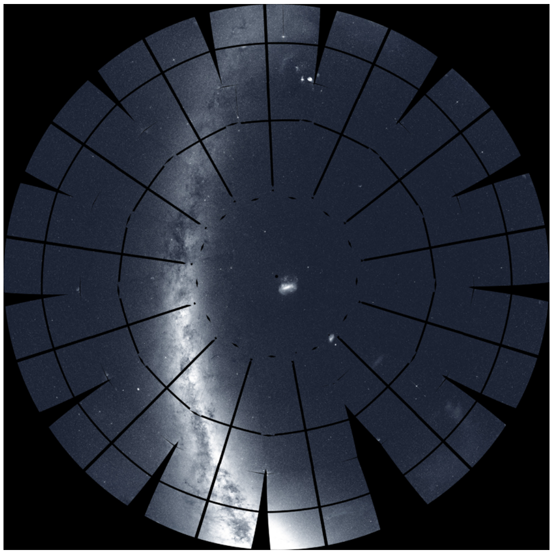


Figure 2 Area of southern sky observed during the first year of operations of TESS. Credit: NASA/MIT/TESS and Ethan Kruse (USRA)

This work will have the following impacts:

- This work will be the first independent large-scale exoplanet search performed on the TESS short cadence (2-min) data. Our algorithm based on joint Bayesian estimation of systematic noise and transit signals (Taaki, Kamalabadi, and Kemball 2020), has demonstrated potential to reveal undetected exoplanets, especially of shorter period or weaker transit signal. This work will also serve as important validation of our algorithmic approach applied at scale to an exisiting data archive.
- Continuous improvements in transit detection methods allow reprocessing of archival exoplanet datasets and push the limits of observable exoplanet populations in current and future observations. Our algorithmic strategy is less sensitive to errors in systematic noise assumptions and are applicable to a broader range of telescopes. This work will advance that important objective.

5 Target Problem

5.1 *Specific research questions*

This proposed allocation will be used to address the following scientific questions:

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[1] Unlike the preceding Kepler mission, each year TESS points at a different set of targets

- **A search for new exoplanets in TESS Yr-1 data:** We propose to deploy our novel Bayesian algorithm (Taaki, Kamalabadi, and Kemball 2020) for the joint detection of systematic noise and exoplanet transit signals on 10,000 target lightcurves observed at short cadence (2-min) in year 1 of operation of the TESS mission. Our prior work demonstrated increased exoplanet detection capability for our joint estimation framework applied to injection tests based on Kepler data. In particular, it showed improved detection of exoplanets: i) with very short orbital periods $P < 5$ days; such transit signals may be masked by high-frequency instrumental noise or stellar variability; and, ii) exoplanets of smaller radius that intrinsically produce very weak signals. Low-radius exoplanets are potential Earth analogs and therefore of critical importance in contemporary exoplanet research.

  Our algorithm is described fully in (Taaki, Kamalabadi, and Kemball 2020), we summarize briefly here for reference. For a lightcurve denoted by $\mathbf{y}$, we jointly model the presence of instrumental noise $\mathbf{l}$ and a stellar signal $\mathbf{s}$. A binary hypothesis test is used to detect the presence of a candidate transit signal $\mathbf{t} \in \mathbf{T}$ in $\mathbf{y}$, the test is defined as:

  $$H_0 : \mathbf{y} = \mathbf{s} + \mathbf{l} \tag{1}$$

  $$H_1 : \mathbf{y} = \mathbf{t} + \mathbf{s} + \mathbf{l} \quad : \quad \mathbf{t} \in \mathbf{T} \tag{2}$$

  We are interested in computing the conditional probability of either hypothesis given the observations, i.e. $p(H_1|\mathbf{y})$ and $p(H_0|\mathbf{y})$, and assessing which is more likely. The detection test is formed as a likelihood ratio test with detection threshold τ:

  $$T(\mathbf{y}) = \frac{p(H_1|\mathbf{y})}{p(H_0|\mathbf{y})} \underset{H_0}{\overset{H_1}{\gtrless}} \tau \tag{3}$$

  Under typical statistical model choices, marginalizing over noise priors to compute the likelihood ratio test reduces to closed form. The noise priors are of the form; $\mathbf{s} \sim \mathcal{N}(0, \mathrm{Cov}_\mathbf{s})$ and $\mathbf{l} = \mathcal{N}(\mathbf{V}\mu_c, \mathbf{V}\mathrm{Cov}_\mathbf{c}\mathbf{V}^\mathbf{T}))$. The detection test is given by:

  $$T(\hat{\mathbf{y}}) = \frac{\hat{\mathbf{y}}^T {\mathrm{Cov}_\mathbf{z}}^{-1}\mathbf{t}}{\sqrt{\mathbf{t}^T {\mathrm{Cov}_\mathbf{z}}^{-1}\mathbf{t}}} \underset{H_0}{\overset{H_1}{\gtrless}} \tau \tag{4}$$

  Where $\mathbf{z} \sim \mathcal{N}(\mathbf{0}, \mathrm{Cov}_\mathbf{s} + \mathbf{V}\mathrm{Cov}_\mathbf{c}\mathbf{V}^\mathbf{T})$ and the detection test is performed on the offset lightcurve $\hat{\mathbf{y}} = \mathbf{y} - \mathbf{V}\mu_c$.

  Joint modelling has two main advantages: i) inadvertent removal of a transit signal in multi-stage pre-processing is less likely occur; and, ii) in a joint stochastic noise model uncertainty in the instrumental noise model and stellar variability can be averaged over via marginalization.

- **Statistical refinement of our joint Bayesian estimation technique:** As noted above, this allocation will be used primarily to search for exoplanet signals in TESS data using the novel detection pipeline developed in our prior work (Taaki, Kamalabadi, and Kemball 2020). However given the new application to TESS data we anticipate the opportunity to develop second-order refinements to our algorithm during early processing without substantially changing the overall framework. These refinements, in and of themselves, will be important research products of this allocation.

5.2 *Scientific and societal impacts*

The detection of new planets in the TESS data will be of considerable intrinsic scientific importance within the astronomy community, particularly as this detector is more sensitive to short-period or low-radius exoplanets. New detections multiply the substantial capital investment in the TESS space mission and increases its overall scientific yield. In addition, exoplanet detections are of considerable public interest and strengthen education and public outreach efforts.

Demonstration of this new algorithm on a larger production run with TESS data will be important additional validation of this method beyond the Kepler injection test results we have already published (Taaki, Kamalabadi, and Kemball 2020). Our algorithmic strategy is less sensitive to assumptions regarding systematic error and inaccurate telescope system data models and are therefore applicable to a broader range of current and future telescopes. The results of this proposal will provide an important test of that key underlying assumption.

Table 1. Transit Search Space

Transit Parameter	Range ($\triangle t_{LC}$)	Step Size ($\triangle t_{LC}$)	Physical Units
Orbital period	$P_{LC} \in [720, 93600]$	5	$P \in [1, 130]$ d
Transit duration	$d_{LC} \in [30, 480]$	$\frac{d_{LC}}{10}$	$d \in [1, 16]$ h
Epoch	$e \in [0,\ P_{LC}]$	5	

Note. — The sample integration time is $\triangle t_{LC} = 2\mathrm{min}$

5.3 *Why Blue Waters?*

With the possibility of petascale computing, a more sophisticated joint estimation method is possible for systematic noise and exoplanet transit signals. This requires computing at the level of Blue Waters but potentially yields a higher detection rate for exoplanets. We discuss the reasons in what follows. In our approach, we form detectors as likelihood ratio tests for a set of candidate transit signals in the presence of additive stellar variability and instrumental noise. Stellar variability statistics are estimated via spectral methods. Instrumental systematics are modelled as a linear reduced dimension model from the shared (co-trending) statistics of the CCD sensor array. As noted above, the detector is of a matched filter form, under Gaussianity assumptions, the computation of which is dominated by the dot product of a candidate transit signal with a non-stationary inverse covariance matrix. Due to the complexity of the joint model, our framework is generally $O(N^2)$ as compared to standard detection methods, which are $O(N)$, where N represents the length of a target star time-series.

In addition to the complexity of our joint signal model, petascale computing is necessary to perform a large-scale planet search due to the resolution of TESS data and resulting dataset size. Performing a transit search using 2-min cadence data (as compared to 30-min data) allows a finer resolution search of candidate transit signals. A resulting increased number of detection tests, as well as increased data length per test, increases the complexity linearly. Other than NASA, no independent high-resolution transit search on TESS short cadence data has been performed.

6 Description of Codes

The codes have been developed and tested on Kepler data on Blue Waters and are immediately transferable to the proposed search of TESS data. The codes implement the algorithm described in (Taaki, Kamalabadi, and Kemball 2020) in optimized Python and largely consist of Numpy operations, in particular slicing and dot products.

The primary kernel computation is a detection test of the form in Equation 4. For each lightcurve, detection tests are computed over a search space of transit signals parameters. TESS data are available in 30-day segments; we independently compute detection tests for a transit signal for each 30-day segment and combine the outputs to compute a detection test for the full 1-year interval. We define an individual computational task as the computation of a complete set of transit detection tests for a single lightcurve over a 30-day segment. We note that all tasks are fully decoupled and require no parallel communication.

In what follows we describe briefly computational design and optimizations developed in our prior development of this code on Blue Waters. All such matrices and vectors in the computation of a detection test over a 30-day segment are of size $N \sim 10^4$.

6.1 *Transit search space*

Compute times and memory requirements scale approximately linearly with the total number of candidate transit signals. The proposed transit parameter search space is summarized in Table 1. For each task, detection tests are computed for $|\mathbf{T}_N| \sim 10^8$ candidate transit signals. This transit search space is based on prior work, consideration of the resolution of TESS data, and the prior search performed by NASA.

Table 2. Major Arithmetic Operations per Task

Computation Type	Per Task per Transit Duration d_{LC}	Per Task
Single Transit Calculations (Additions)	$S_{d_{LC}} = \frac{N^2 \cdot d_{LC}}{e} \approx 10^{10}$	$\prod_{d_{LC} \in D} S_{d_{LC}} \approx 10^{11}$
Transit Detection (Dot Products)	$M_{d_{LC}} = N \cdot \vert \mathbf{T}\vert_{d_{LC},N} \vert \approx 10^{11}$	$\prod_{d_{LC} \in D} M_{d_{LC}} \approx 10^{12}$

Note. — 1) $\mathbf{T}|_{d_{LC},N}$ is the restriction of the transit search space $\mathbf{T}$ to fixed duration d_{LC} and length N; 2) A task is the the computation of a complete set of transit detection tests for a single lightcurve in a 30-day TESS data segment.

Table 3. Memory Resources Per Task

Resource Type	Resources per Task
Total Remote Disk Access (read)	6 MB
Total Remote Disk Access (write)	160 MB
Read Count	1
Write Count	10^8
Local Memory	1.4 GB

6.2 *Detection test codes*

Referring to Equation 4, each detection test for a transit signal utilizes an inverse covariance matrix ${\mathrm{Cov}_{\mathbf{z}}}^{-1}$. The covariance $\mathrm{Cov}_{\mathbf{z}}$ depends on the lightcurve $\mathbf{y}$, but not on the transit signal under consideration. Therefore the inverse is only computed once per task. This does not represent a significant aspect of computation ($< \frac{1}{5}$ of core hours for a task). However this matrix is held in memory throughout the computation of the detection tests and is generally $\sim$ 0.8 GB in size.

The detector involves the computation of a matrix-vector product ${\mathrm{Cov}_{\mathbf{z}}}^{-1}\mathbf{t}$ of $O(N^2)$. We efficiently implement the computation of many of these calculations for a large number of candidate transit signals $\mathbf{t} \in \mathbf{T}$ by exploiting similarities between transit signals. Candidate transit signals are represented by a signal that is zero everywhere except on disjoint in-transit cadences. As such a candidate transit signal may be efficiently decomposed into a number of disjoint in-transit events, each of which is supported on a small interval $d_{LC} \ll N$ (d_{LC} represents the transit duration). The matrix-vector product of a single in-transit event can then be efficiently computed via Numpy slicing and an addition operation of $O(d_{LC} \cdot N)$. Single transit calculations are then stored to compute detection tests for a range of candidate transit signals of fixed in-transit duration d_{LC}. The approximate number and type of major arithmetic computations for a task are summarized in Table 2 for the transit search space in Table 1.

This optimized computation allows us to improve the $O(N^2)$ complexity of the detector in raw form, albeit by increasing the memory requirements. The memory required to hold single transit calculations for a task is of order $\sim$ 0.4[GB].

A single remote memory read of 6 MB is performed once at the beginning of a task and remote memory writes of 4 B occur at the end of every transit test computation (therefore 10^8 writes per task). No communication is needed between tasks. The individual detection results are intermediate as they are combined to form composite detection statistics as described below. Memory and I/O requirements (remote and local) per task are summarized in Table 4.

After each task corresponding to a single 30-day lightcurve segment are complete (12 tasks per 1-year lightcurve), the detection statistics are combined to compute overall detection statistics for all candidate transit signals for the entire year. The detection tests are output for the year requiring 0.2 GB per lightcurve. These are checked to find candidate signals above a detection threshold. We propose to search the first year of data for a total of $10,000$ targets. A total of 2 TB of storage is needed for the detection tests for the full set of lightcurves.

7 Experience / Readiness of Codes

The same data infrastructure and processing was developed by NASA for both Kepler and TESS, as such the data format and properties are very similar. All our codes are readily transferable to TESS data with minor alterations. Our code has already been used on Blue Waters to successfully search for exoplanets in a very short segment of Kepler data (in addition to injection tests). We have conducted successful preliminary tests on Blue Waters with TESS data while drafting this proposal.

In order to fully optimize our detection performance, some initial experimentation would be prudent to determine an optimal transit search space and stellar variability model. This should represent a relatively small amount of calendar time and allocated node hours ($< 5\%$) based on similar data exploration performed for prior work. This project is funded by internal UIUC funds. No detailed technical or further support from Blue Waters is necessary. Given our previous work on Blue Waters we estimate the following breakdown of our requested allocation per quarter (Q1: 50%, Q2: 50%). We plan to use quarter 1 to investigate optimal transit search space and stellar/instrumental model, and begin the proposed transit search. We plan to use quarter 2 to complete the transit search.

8 Past Usage

Neither Co-I Taaki or Kamalabadi have received prior allocations on Blue Waters. Kemball is a Blue Waters Professor (BWP) with current allocation ILL_bbao and has never previously applied for a UIUC allocation. This BWP project is motivated by the data- and compute-intensive challenges posed by the large-survey telescopes of the coming decade, including the Large Synoptic Survey Telescope (LSST) and the Square Kilometer Array (SKA) amongst others. The science goals of these telescopes require high data acquisition rates and concomitant innovations in data analysis methods, some very compute-intensive and requiring resources on the scale of Blue Waters. This allocation, and its predecessors, have been used to support the existing thesis research by Jamila Taaki in exoplanet detection under the thesis co-advisor relationship.

Recent publications derived from this BWP allocation include:

- Wen, D. 2020, Ph.D. Thesis, The Distribution of Dark Matter at Large Scales and in Gravitational Lenses, (UIUC:Astronomy)
- Taaki, Kamalabadi, and Kemball, 2020, Bayesian Methods for Joint Exoplanet Transit Detection and Systematic Noise Characterization, Astronomical Journal, (DOI: 10.3847/1538-3881/ab8e38)
- Wen, Kemball, and Saslaw, 2020, Halo counts-in-cells for cosmological models with different dark energy, Astrophysical Journal, (DOI: 10.3847/1538-4357/ab6d6f)
- Tobin, T. 2019, Ph.D. Thesis, Observational and Theoretical Studies of SiO Maser Polarization toward Late-type Evolved Stars, (UIUC: Astronomy).

9 Resources Required

We performed a preliminary computational study using our codes on Blue Waters for TESS data to obtain accurate time and memory allocation requirements for the scientific objectives outlined in this proposal. We break down these requirements per task. As defined above, a task corresponds to the computation of a complete set of transit detection tests for a single lightcurve for a 30-day segment of TESS data.

Each task is highly parallel, no communication is needed between tasks apart from aggregation of detection statistics; this has minimal impact on the parallel decomposition of the problem. Even though the problem is not tightly coupled it does require computational resources on the scale of Blue Waters however. The tasks corresponding to a single lightcurve are computed contemporaneously so that their transit statistics may be combined and the output data from the individual tasks discarded; close synchronization is not required beyond this. Transit searches for different lightcurves may be completed in any order.

Our 10,000 TESS targets require 120,000 tasks as each lightcurve consists of twelve 30-day segments. Based on our empirical measurements, we request 6000 XE nodes, placing 20 tasks per node and one core per task in order to avoid a memory bottleneck. Each task takes 40 core hours to complete, therefore 20 tasks on a single node require 40 node hours (NH). We request a total of 250,000 NH. Table 4 contains a breakdown of resources per task and node.

Less than 1 TB of Lustre storage is needed at any one time, to hold the intermediate outputs of tasks before combining detection statistics. Storage of all the final detection statistics amounts to 2 TB which can be stored within the default project disk allocation; we request no further storage from Blue Waters beyond the default allocation.

Table 4. Resources per Node

Resource Type	Resources per Task	Resources per Node
Total Remote Disk Access (read)	6 MB	120 MB
Total Remote Disk Access (write)	160 MB	3.2 GB
Read Count	1	20
Write Count	$\sim 10^8$	$\sim 2 \cdot 10^9$
Local Memory	1.4 GB	< 32 GB
Compute	40 core hours	40 NH

10 Data Management at Project End

As Blue Waters nears the project end, the output data 2 TB will be moved to an external location in Astronomy or ECE. All other data is to be discarded.

11 Requested start date and duration

Requested start date: Jan 1st with a default duration of 12 months.

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