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Jérôme Berthier, B Carry, F Vachier, S Eggl, A Santerne. Prediction of transits of solar system objects in Kepler /K2 images: An extension of the Virtual Observatory service SkyBoT. Monthly Notices of the Royal Astronomical Society, 2016, 457 (3), 10.1093/mnras/stw492 . hal-01278026

HAL Id: hal-01278026

<https://hal.science/hal-01278026>

Submitted on 23 Feb 2016

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Prediction of transits of solar system objects in *Kepler*/K2 images: An extension of the Virtual Observatory service SkyBoT

J. Berthier,¹★ B. Carry,^{1,2} F. Vachier,¹ S. Eggl,¹ and A. Santerne,³

¹*IMCCE, Observatoire de Paris, PSL Research University, CNRS, Sorbonne Universités, UPMC Univ Paris 06, Univ Lille, France*

²*Laboratoire Lagrange, Université de Nice-Sophia Antipolis, CNRS, Observatoire de la Côte d’Azur, France*

³*Instituto de Astrofísica e Ciências do Espaço, Universidade do Porto, CAUP, Rua das Estrelas, 4150-762 Porto, Portugal*

Accepted XXX. Received YYY; in original form ZZZ

ABSTRACT

All the fields of the extended space mission *Kepler*/K2 are located within the ecliptic. Many solar system objects thus cross the K2 stellar masks on a regular basis. We aim at providing to the entire community a simple tool to search and identify solar system objects serendipitously observed by *Kepler*. The SkyBoT service hosted at IMCCE provides a Virtual Observatory (VO) compliant cone-search that lists all solar system objects present within a field of view at a given epoch. To generate such a list in a timely manner, ephemerides are pre-computed, updated weekly, and stored in a relational database to ensure a fast access. The SkyBoT Web service can now be used with *Kepler*. Solar system objects within a small (few arcminutes) field of view are identified and listed in less than 10s. Generating object data for the entire K2 field of view (14°) takes about a minute. This extension of the SkyBot service opens new possibilities with respect to mining K2 data for solar system science, as well as removing solar system objects from stellar photometric time-series.

Key words: (stars:) planetary systems – minor planets, asteroids – ephemerides – virtual observatory tools

1 INTRODUCTION

The NASA Discovery mission *Kepler* was launched in 2009, with the aim of detecting exoplanets from the photometric signature of their transit in front of their host star (?). Following the second failure of a reaction wheel in May 2013, the original field of view (FoV) in Cygnus could not be fine pointed anymore. An extension of the mission, dubbed K2 (?), was designed to be a succession of 3-month long campaigns, where the spacecraft’s FoV scans the ecliptic plane. This mode of operations implies that many solar system objects (SSOs) cross the subframes centered on K2 mission targets. Following a visual inspection of the K2 engineering FoV, ? reported that SSOs had crossed half of the 300 stars monitored over the 9 days of engineering observations.

Owing to the large number of stellar targets in each K2 campaign, the likelihood of observing SSOs at any single epoch is indeed high. Given a typical mask size around each

target of 15x15 pixels or 1x1 arcmin for between 10,000 and 30,000 stellar targets, the filling factor¹ of K2 entire FoV ranges from 3% to 10% (Table 1). A corresponding fraction of the SSOs that cross K2 FoVs are within a target mask at each instant, from a few tens of minutes for a near-Earth object to approximately 6h for a main-belt asteroid, and up to several days for a Trojan or a transneptunian object. Over a whole campaign, the cumulative probability to observe these SSOs get close to one, as the different target masks, stacked over ecliptic longitude, almost fill entirely the range of ecliptic latitudes within K2 field of views (Table 1). Each SSO has thus only a few percent chance to dodge all the target masks as it crosses K2 field of view (Table 1). Several programs dedicated to planetary science have been already carried out by K2, like characterization of the rotation period of transneptunian objects (?). The giant planet Neptune and its satellites were also observed in C3, and Uranus will be in C8.

Considering the typical magnitude of K2 stellar targets

★ E-mail: berthier@imcce.fr

¹ The fraction of the K2 FoV that is actually downlinked.

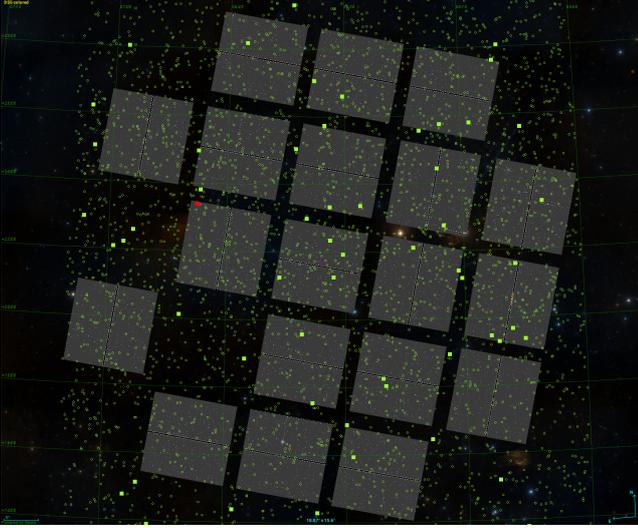


Figure 1. K2 full frame image taken on 2014, March, the 11th, at 23:27:23.77 UTC (mid-exposure), over-plotted on the DSS colored view, displayed by Aladin. All the 3136 known SSOs brighter than $V \leq 20$ (among 9702) present within the FoV reported by SkyBoT are represented, by the green circles for asteroids (and solid squares for $V \leq 16.5$), and by the red dot for a comet (84P, $V = 18.8$).

(80% of the stars have a $V \leq 15-16$), and the typical K2 photometric precision of a few hundreds ppm, many SSOs will be imaged together with the stars. At any instant several thousands of SSOs with $V \leq 20$ lay within K2 entire field of view (e.g., Fig. 1). A magnitude 20 asteroid will contribute to the star signal at a level of 1000 ppm, and is, therefore, easily detectable.

There is a twofold interest in having a simple tool to predict *encounters* between stars and SSOs:

- The K2 community profits from identifying any encounters that add undesirable signals, hence photon noise, to stellar light curves, at non-negligible levels.
- The solar system community profits, as each encounter provides a short light curve (typical a couple of hours) of an SSO with excellent photometric accuracy. On average, ten encounters per campaign can be expected (Table 1).

To cater to those demands, we present an extension of our Virtual Observatory (VO) tool SkyBoT (?), hosted at IMCCE. This tool is web based, open-access, and provides a simple way to identify all the SSOs present within a field of view at a given epoch. This article is organized as following: in Section 2 we describe the SkyBoT service, its algorithm and access, and we show a pair of examples in Section 3.

2 SKYBOT: THE VO SKY BODY TRACKER

The typical queries to astronomical catalogs are so-called *cone searches*, in which all targets within a given field of view are returned. This is mostly adapted to objects with fixed coordinates, such as stars and galaxies, their parallax and proper motion being much smaller than the field of view.

Table 1. Number of K2 stellar targets, fraction of the total field of view downlinked to Earth, filling fraction of ecliptic latitudes (β_f), expected average number and standard deviation of stellar encounters for each SSO (μ_e and σ_e), for each campaign (up to C7).

Campaign	Targets	Area (%)	β_f (%)	μ_e	σ_e
C0	7756	2.90	94.16	4.3	2.7
C1	21647	8.09	98.25	11.8	5.4
C2	13401	5.01	96.53	7.4	4.4
C3	16375	6.12	97.94	9.1	4.8
C4	15781	5.90	98.18	8.7	4.2
C5	25137	9.40	98.68	13.8	6.3
C6	27289	10.20	98.91	14.9	6.2
C7	13261	4.96	96.74	7.3	4.9

But the coordinates of objects in our solar system constantly change and cone searches cannot use pre-defined catalogs. As a result, most tools for source identification fail to associate the observed SSO with a known source. The SkyBoT service provides a solution by pre-computing ephemerides of all the known SSOs, and storing them in a relational database for rapid access upon request.

2.1 Ephemerides computation and SkyBoT algorithm

Among other services, the Institut de mécanique céleste et de calcul des éphémérides (IMCCE) produces the French national ephemerides under the supervision of the Bureau des longitudes. The development and maintenance of ephemerides tools for the astronomical community is also a part of its duties. As such, the institute offers online computation of solar system object ephemerides through a set of Web services².

The ephemerides of planets and small solar system objects are computed in the ICRF quasi-inertial reference frame taking into account perturbations of the 8 planets, and post-Newtonian corrections. The geometric positions of the major planets and the Moon are provided by INPOP planetary theory (?). Those of small SSOs (asteroids, comets, Centaurs, trans-neptunian objects) are calculated by numerical integration of the N-body perturbed problem (Gragg-Bulirsch-Stoer algorithm, see ??), using the latest published osculating elements, from the *astorb* (?) and *cometpro* (?) databases. The overall accuracy of asteroid and comet ephemerides provided by our services are at the level of tens of milli-arcseconds, mainly depending on the accuracy of the minor planet's osculating elements. The positions of natural satellites are obtained thanks to dedicated solutions of their motion, e.g. ??? for Mars and Jupiter, ? for Saturn, ? for Uranus, and ? for Neptune's satellites.

The ephemerides of all the known objects of our solar System are recomputed on a weekly basis, for a period

² <http://vo.imcce.fr/webservices/>

which extends from the end of the 19th century (1889-11-13) to the first half of the 21st century (2060-03-21), and stored with a time step of 10 days in a hierarchical tree structure supported by nodes based on geocentric equatorial coordinates. For each cone search, this database is queried, and all the targets expected to be within the field of view are listed. Their topocentric ephemerides for the exact requested time are then computed on the fly.

The apparent topocentric celestial coordinates (i.e. relative to the true equator and equinox of the date) are computed by applying light aberration, precession, and nutation corrections to the observer-target vector. The coordinates of the topocenter can either be provided directly by users (longitude, latitude, altitude), or by using the observatory code provided by IAU Minor Planet Center³ for listed observatories.

The SkyBoT service was released in 2006 (?). It is mostly used to identify moving objects in images (e.g. ???), and data mining of public archives (e.g. ???). It responds to about 80,000 requests every month (more than 18 millions in 7 years), and has a typical response time of less than 10 s for 95% of requests.

2.2 An extension to non Earth-bound geometries

Owing to the large number of known SSOs (currently 700,000), and the extended period of time that needs to be covered (from the first photographic plates to the present), pre-computations are the key to a timely service. As the database of pre-computed ephemerides was ordered in a tree based on equatorial coordinates (RA/Dec) to allow quick identification of potential targets within a field of view, the service was limited to a single geometry. The large parallax presented by objects within the solar system indeed implies different equatorial coordinates depending on the position of the observer. The first releases of SkyBoT were thus limited to Earth geocenter, topocenters, and low-orbit satellites such as the Hubble Space Telescope or the International Space Station.

In 2010, we started a new phase of the SkyBoT development to allow the use of its cone-search method from other geometries. This was motivated by availability of wide-field ($2^\circ \times 2^\circ$ and $10^\circ \times 10^\circ$) images taken by the OSIRIS camera on-board the ESA *Rosetta* mission, which is on an interplanetary trajectory crossing the asteroid main-belt, between Mars and Jupiter. The great distance between the probe and the Earth, combined with the proximity of SSOs implied observing geometries so different that the Earth-bound database could not be used to search for and identify targets correctly. This challenge was recently solved. An example validating the corresponding update of the SkyBoT service is presented in Fig. 2.

To preserve the fast response time of the service, a switch was set in place, to redirect queries to different databases, one for each space probe. These databases have

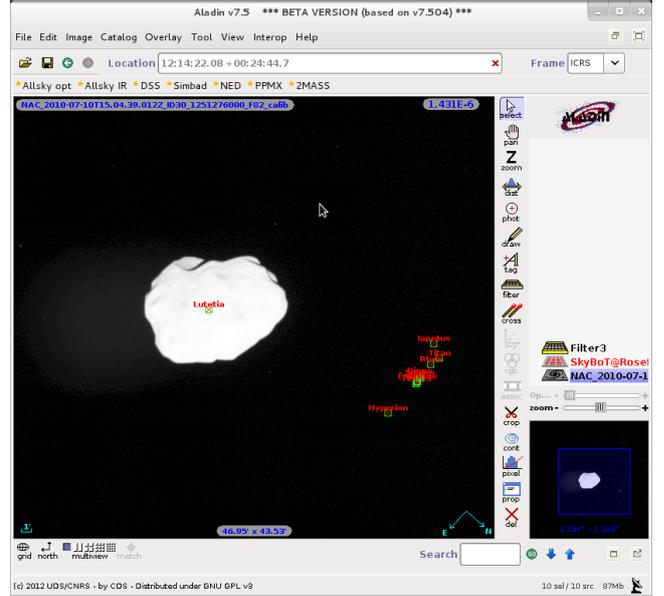


Figure 2. OSIRIS NAC image taken during the flyby of asteroid (21) Lutetia by ESA *Rosetta* space mission, on 2010, July, the 10th, at 15:04:30 UTC (?), displayed in Aladin. A SkyBoT cone-search query correctly lists Lutetia, together with Saturn and its satellites imaged in the background. Considering their dramatic difference of distance to *Rosetta* (36,000 km and 6.8 au respectively), this example validates the SkyBoT upgrade to space missions.

smaller time coverage, corresponding only to the mission lifetimes. The weekly computation of ephemerides is, therefore, not as CPU intensive as for the main (Earth) database. There are currently two space probes available: *Rosetta* and *Kepler*. The architecture of SkyBoT after the update is such that we can add more space probes upon request: any space mission located on a Earth leading or trailing orbit (e.g. Herschel), or at L2 point (e.g. JWST, Euclid), or on an interplanetary trajectory (e.g. Cassini, JUNO) could be added, if desired by the community.

2.3 Access to the service

There are several ways to use the SkyBoT Web service. Users who may want to discover the service can use a simple query form on the IMCCE's VO SSO portal⁴ or the well-established Aladin Sky Atlas (?). The service is also fully compliant with VO standards, and thus, can be scripted in two different ways: a) by writing a client to send requests to the SkyBoT server and to analyze the response, or b) by using a command-line interface and a data transfer program such as `curl` or `wget`.

In all cases, three parameters must be passed to SkyBoT: the pointing direction (RA/Dec), the epoch of observation, and the size of the field of view. The typical response time for request from K2 point of view are of a few seconds

³ <http://www.minorplanetcenter.net/iau/lists/ObsCodesF.html>

⁴ <http://vo.imcce.fr>

for small field of view (target mask), and of about 1 min for the entire field of view of *Kepler* of about 14° .

3 SOME EXAMPLES

We now present a couple of examples of the typical usage of the SkyBoT service for K2. In Fig. 1, we show a full frame image from C0, together with the result of a SkyBoT request: among the 9702 SSOs located in the FoV at that time, 3136 are brighter than $V \leq 20$, and about 50 are brighter than $V \leq 16$, thus potentially observable by K2. In Fig. 3, we present the light curve of the star EPIC 201872595 ($K_p = 12.2$) from Campaign #1, in which each surge of flux is caused by the transit of a different SSO within the target mask. The stellar flux is clearly contaminated by the SSOs. This is an obvious case of transits by SSOs, each being barely less bright ($V \sim 14-15$) than the target star. Fainter SSOs ($V \sim 18-19$) still affect stellar light curves, without being easily identifiable by naked eye. Using the SkyBoT service, it is easy to check any suspicious point in a stellar light curve, by performing a cone-search, centered on the star, at the time of the corresponding photometry measurement, with a narrow field of view of a few arcseconds corresponding to the apparent size of the stellar mask.

The service also allows to hunt for photometric data of SSOs. One can use SkyBoT to get the list of all the SSOs within the K2 entire FoV for each campaign, and compute their encounters with target stars to extract their photometry. For the fast generation of detailed ephemerides for each target, we recommend the use of our Miriade service (?). Requesting SkyBoT cone-search for the entire FoV, with a time step of 30 min during a whole campaign, is more CPU intensive than computing the same ephemerides for only the identified targets with Miriade.

In Fig. 4 we present 10 light curves of asteroid (484) Pittsburghia (apparent magnitude ~ 15) we measured in K2 Campaign #0. The light curves have been constructed following the steps described above: a global SkyBoT request, followed by a Miriade generation of ephemerides every 30 min for Pittsburghia, and finally a check of whenever the asteroid was within one of the stellar masks. The synthetic light curve was generated using the 3-D shape model of Pittsburghia by ? and ? is overplotted to the data. The excellent match of the photometry measured on K2 frames with the shape models illustrate the interest of data mining K2 data archive for SSO period determination, and shape modeling.

4 CONCLUSION

We present a new version of the Virtual Observatory Web service SkyBoT. Its cone-search method allows to list all the solar system objects present within a given field of view at a given epoch, as visible from the Earth, the ESA *Rosetta* mission, and now the NASA *Kepler* telescope. More space missions can be added upon request, if desired by the community. Typical queries over limited field of views take less

than 10s, while queries over extended field of view such as *Rosetta*/OSIRIS camera or *Kepler* full CCD array take about a minute. Possible applications of SkyBoT for K2 data are presented, and the results illustrate the interest of K2 for studying asteroids spin, period, and shapes from the light curves which can be extracted from K2 data. Their analysis and interpretation will be presented in a forthcoming paper (Carry et al., in preparation).

ACKNOWLEDGEMENTS

We acknowledge support of the ESAC Faculty for J. Berthier's visit. This research has received funding from the European Union's H2020- PROTEC-2014 - Protection of European assets in and from space project no. 640351 (NEOSShield-2). A. Santerne is supported by the European Union under a Marie Curie Intra-European Fellowship for Career Development with reference FP7-PEOPLE-2013-IEF, number 627202. He also acknowledges the support from the Fundação para a Ciência e Tecnologia, FCT (Portugal) in the form of the grants UID/FIS/04434/2013 (POCI-01-0145-FEDER-007672) and POPH/FSE (EC) by FEDER funding through the program "Programa Operacional de Factores de Competitividade - COMPETE".

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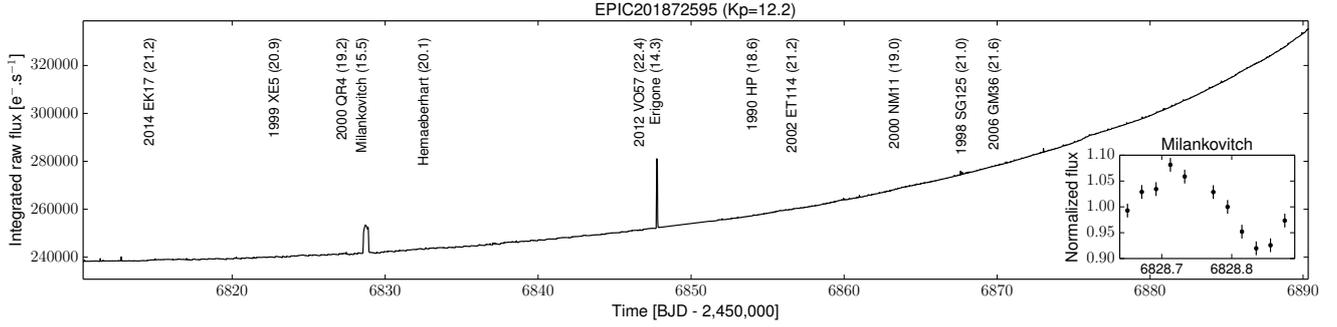


Figure 3. K2 raw light curve integrated over all pixels of the target EPIC 201872595 ($K_p = 12.2$) observed during Campaign #1. The increase in flux along the campaign is a systematic effect. The predicted transits of known SSOs down to magnitude 22.5 together with their expected V magnitude. The transit of two relatively bright SSOs, (1605) Milankovitch and (163) Erigone, are clearly visible. The fainter SSOs also imprint a significant increase in the observed flux as they pass into the target imargette. The inset in the bottom right is a zoom on the transit of (1605) Milankovitch. It displays the target-corrected and normalized flux of the SSO, and highlights the phase rotation of the SSO.

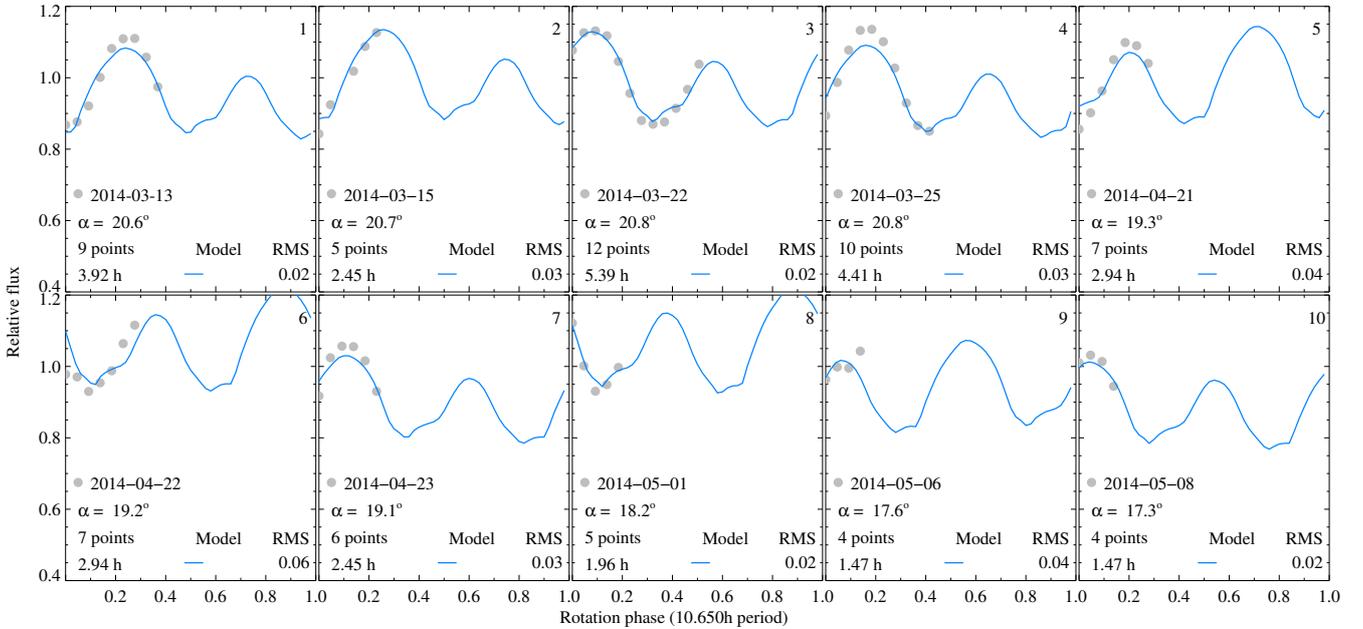


Figure 4. Example of asteroid light curves retrieved from K2 images. The grey dots represent the measured photometry of (484) Pittsburghia, and the blue curves stand for the synthetic light curves obtained from the 3-D shape model of the asteroid by ? and ?. The residuals between observed and modeled points are of 0.03 magnitude on average, as reported on each graph.

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