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GALEXTIN: an alternative online tool to determine the interstellar extinction in the Milky Way

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ABSTRACT

Estimates of interstellar extinction are essential in a broad range of astronomical research. In the last decades, several maps and models of the large-scale interstellar extinction in the Galaxy have been published. However, these maps and models have been developed in different programming languages, with different user interfaces and input/output formats, which makes using and comparing results from these maps and models difficult. To address this issue, we have developed a tool called GALEXTIN (<http://www.galexlin.org>), which estimates interstellar extinction based on both available 3D models/maps and 2D maps. The user only needs to provide a list with coordinates (and distance) and to choose a model/map. GALEXTIN will then provide an output list with extinction estimates. It can be implemented in any other portal or model that requires interstellar extinction estimates. Here, a general overview of GALEXTIN is presented, along with its capabilities, validation, performance and some results.

Key words: methods: miscellaneous – astronomical data bases: miscellaneous – virtual observatory tools – software: development – dust, extinction – ISM: structure.

1 INTRODUCTION

An estimation of interstellar extinction is key across many areas of Astronomy, including in stellar studies, where it affects the measurement of intrinsic fluxes and circumstellar reddening, in the structure of our Galaxy, where it affects the determination of distances and other properties, and in extragalactic studies. In the latter case, it is necessary to estimate the contribution of the extinction of our Galaxy along all line of sight. All these investigations require knowledge of extinction towards given objects from their coordinates and distances (for 3D models). Despite the difficulty in modelling extinction owing to its clumpy distribution, many 3D models and 2D maps have been developed in the last three decades for describing the dust distribution in our Galaxy. For detailed reviews of the studies modelling Galactic extinction, see the introductions in the works by Amôres & Lépine (2005, hereafter AL), Marshall et al. (2006), Robin (2009), Nidever, Zasowski & Majewski (2012), Robin et al. (2015), Sale (2015), Green et al. (2015), and Bovy et al. (2016).

Burstein & Heiles (1978, 1982) based on H I galaxy counts produced maps used to predict the integrated Galactic reddening covering a large area in the sky. They were one of the most traditional and utilized maps until the end of the 1990s. Schlegel, Finkbeiner & Davis (1998) developed maps of the far-infrared emission from dust employing the Cosmic Background Explorer (COBE)/Diffuse Infrared Background Experiment (DIRBE) data (Kelsall et al. 1998). In Schlegel et al. (1998), reddening is determined both from the flux density at 100 μm and from a temperature-correction map. These maps have a massive usage in Astronomy, with over 15 000 citations. Nevertheless, Arce & Goodman (1999), Chen et al. (1999) and Amôres & Lépine (2005), among others, have pointed out that the extinction values in those maps are overestimated towards some directions, mainly towards regions with $A_V > 0.5$ mag. Drimmel, Cabrera-Lavers & López-Corredoira (2003) formulated a model to describe the 3D extinction in the Galaxy considering the Galactic dust distribution of Drimmel & Spergel (2001) that uses COBE/DIRBE data.

Amôres & Lépine (2005), developed two models to describe the interstellar extinction in the Galaxy, considering the distribution for H I and H₂. In their first model, the Galaxy is axisymmetric (ALA), and extinction increases linearly as a function of distance. In the

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second model (ALS), the extinction increases abruptly on paths passing through spiral arms. The representation of spiral arms is based on fitting ℓ - v diagrams to the distribution of H I and H II regions, and comparing the model density estimates as a function of Galactic longitude with those from H I surveys and The Infrared Astronomical Satellite (*IRAS*) data (Neugebauer et al. 1984) fluxes at 100 μ m as tracers of dust and CO, respectively. They also compared their models for a wide range of distances and directions with catalogues such as Neckel & Klare (1980), Savage et al. (1985) and Guarinos (1992). Amôres & Lépine (2005) estimated that, on average, Schlegel et al. (1998) overestimate the extinction by approximately 20 per cent.

Later, Amôres & Lépine (2007) revised their ALA model in order to achieve better estimates at intermediate and high Galactic latitudes. They calibrated their model with a sample of elliptical galaxies from Burstein (2003). They also compared their model predictions with open and globular clusters, as well as with the extinction at the Galactic Centre.

Dobashi et al. (2005) provided a map for A_V covering Galactic longitudes ($0^\circ \leq \ell \leq 360^\circ$) within ($|b| \leq 40^\circ$) based on Digitized Sky Survey I (DSS) data (Lasker 1994) star counts. The maps are available in both high (6 arcmin) and low (18 arcmin) resolution. Afterwards, using The Two Micron All Sky Survey (2MASS) star counts and the Besançon Galaxy Model (BGM), Dobashi et al. (2013) rendered maps with two resolutions, 1 and 15 arcmin, respectively.

Marshall et al. (2006) used the BGM (Robin et al. 2003, 2016; Amôres, Robin & Reylé 2017) and 2MASS data (Skrutskie et al. 2006) to build a model aimed at describing interstellar extinction in three dimensions. The map coverage is $|\ell| \leq 100^\circ$ for $|b| < 10^\circ$ for several lines of sight.

Chen et al. (2013) assumed a similar method and combined the VISTA Variables in the Via Lactea (VVV) data (Saito et al. 2012), 2MASS and Galactic Legacy Infrared Midplane Survey Extraordinaire (GLIMPSE) data (Churchwell et al. 2009) to derive the extinction towards the Galactic bulge for planar regions, namely $|\ell| \leq 10^\circ$ for $|b| \leq 2^\circ$. In a subsequent work, Schultheis et al. (2014) extended the latitude coverage to $-10^\circ < b < 5^\circ$.

Rowles & Froebrich (2009) developed All-Sky extinction maps $|b| \leq 30^\circ$ based on the median near-infrared colour excess technique with 2MASS data. Gonzalez et al. (2011) elaborated a method for obtaining reddening maps using the mean $J - K_s$ colour of red clump (RC) stars based on VVV data. Later, Gonzalez et al. (2012) applied this method to the entire bulge observed by VVV, deriving maps with a resolution of 2 and 6 arcmin.

Schlaflly et al. (2010) checked the reddening law and the accuracy of the Schlegel et al. (1998) maps employing Sloan Digital Sky Survey (SDSS) photometry (Abazajian et al. 2009). They reported that Schlegel et al. (1998) overestimated $E(B - V)$ by 14 per cent. Later, Schlaflly & Finkbeiner (2011) validated this result and calibrated the Schlegel et al. (1998) maps applying the Fitzpatrick & Massa (2005) extinction law and SDSS data. They also implemented a useful table (table 6 in their paper) to achieve the conversion from $E(B - V)_{\text{SFD}}$ to $E(B - V)$ for roughly 100 passbands and four R_V values, in which SFD means Schlegel, Finkbeiner & Davis (1998).

Using the Xuyi Schmidt Telescope Photometric Survey (Zhang et al. 2014) of the Galactic Anticentre, Chen et al. (2014) derived a 3D extinction map in the r band for the Galactic anticentre with coverage for Galactic longitude $140^\circ < \ell < 240^\circ$ and latitude $-60^\circ < b < 40^\circ$. Schlaflly et al. (2014), based on a sample of 500 million stars of Pan-STARRS 1, hereafter PS1 (Kaiser et al. 2010) for the northern sky, derived a map of dust reddening up to 4.5 kpc for

two resolutions, 7 and 14 arcmin. Sale et al. (2014) handled The INT Photometric H α Survey of the Northern Galactic Plane (IPHAS) data (Drew et al. 2005) with a hierarchical Bayesian model (Sale 2012) to derive interstellar extinction for the entire northern Galactic plane, $30^\circ \leq \ell \leq 230^\circ$ ($|b| < 5^\circ$).

The observations performed by the *Planck* satellite (Planck Collaboration et al. 2014a) have been important for modelling and obtaining all-sky parameters of thermal dust emission (Planck Collaboration et al. 2014b). Furthermore, Planck Collaboration et al. (2014b) provided the values of several properties of dust emission, namely the dust temperature, dust optical depth at 353 GHz (τ_{353}), dust spectral index, dust radiance, and $E(B - V)$ estimates for extragalactic studies, among others. Planck's Dust Model Page (see Table 1) contains individual files for each of these five parameters.

Green et al. (2015) presented a 3D interstellar extinction map based on PS1, and 2MASS data for three-quarters of the sky. Using a similar method, Green et al. (2018) produced a new 3D map of interstellar extinction based on stellar photometry from PS1 and 2MASS. The map covers approximately three-quarters of the sky (declinations with magnitudes for $\delta \geq -30^\circ$). They also derived another 3D map (Green et al. 2019) based on *Gaia*-DR2 (Gaia Collaboration et al. 2018) that covers the sky north of declination -30° . The results can be obtained through an interface (as shown in our Table 1) written in PYTHON. They also provide a catalogue containing the distances, reddenings and types of 799 million stars. In the work by Hanson et al. (2016), the authors use both PS1 and *Spitzer*/GLIMPSE (Churchwell et al. 2009) data to develop a 3D map with an angular resolution of 7 arcmin towards $0^\circ < \ell < 250^\circ$ for $|b| \leq 4.5^\circ$.

Capitanio et al. (2017) developed 3D extinction maps based on a regularized Bayesian inversion of individual colour excess data. In a previous work (Lallement et al. 2014), these authors had developed a 3D model based on the inversion method employing a sample of 23 000 stars within 2.5 kpc. Later, Lallement et al. (2019) rendered 3D maps based on both 2MASS and *Gaia*-DR2 data applying Bayesian inversion. Chen et al. (2019) derived a 3D map based on 2MASS, *Gaia*-DR2, and spectroscopic survey data using a machine-learning algorithm (Random Forest regression). Soto et al. (2019) derived a map for a colour-excess extinction using VVV and GLIMPSE data towards, $295^\circ \leq \ell \leq 350^\circ$ at Galactic latitudes ($|b| < 1^\circ$), in some cases going up to $|b| < 2^\circ$ and covering 148 square degrees. The authors used the Rayleigh-Jeans Colour Excess (RJCE) technique.

Babusiaux et al. (2020) developed a Bayesian deconvolution method to compute distance and interstellar extinction using 2MASS, The UKIRT Infrared Deep Sky Survey (UKIDSS) data (Lawrence et al. 2007) and *Gaia*-DR2 data. In another work (Hottier, Babusiaux & Arenou 2020), they applied a technique called Field Extinction-Distance Relation Deconvolver (FEDReD) to elaborate a map of interstellar extinction based on 2MASS and *Gaia*-DR2, which covers the entire Galactic disc ($|b| \leq 0.^\circ 24$), reaching distances up to 5 kpc in the direction of the Galactic Centre. Guo et al. (2021) derived a 3D interstellar extinction map for the southern sky covering 14 000 square degrees. They used the SkyMapper Southern Survey (Wolf et al. 2018) with *Gaia*-DR2, 2MASS and Wide-field Infrared Survey Explorer (WISE) data (Wright et al. 2010).

Regarding the estimation of interstellar extinction by users, there are a number of tools for computing extinction, either as programs to run on the user's computer or as on-line services. Table 1 gives a list of these services as well as their links.

Table 1. List of available sites and services that estimate the interstellar extinction/reddening in our Galaxy.

Service/repository	Link
A tridimensional model of the Galactic interstellar extinction (Arenou et al. 1992)	http://www.whip.obspm.fr/cgi-bin/afm
Galactic extinction calculator (Schlegel et al. 1998; Schlafly & Finkbeiner 2011)	https://ned.ipac.caltech.edu/forms/calculator.html
and coordinate transformation	
2D maps based on DSS and 2MASS data (Dobashi et al. 2005; Dobashi 2011; Dobashi et al. 2013)	http://darkclouds.u-gakugei.ac.jp/
Models for interstellar extinction in the Galaxy (Amôres & Lépine 2005)	http://gal extin.org/amores.lepine.php
All-sky maps (Rowles & Froebrich 2009; Dobashi et al. 2005; Schlegel et al. 1998)	http://astro.kent.ac.uk/~df/query_input.html
and smaller-scale maps (Lombardi et al. 2006, 2008; Cambrésy 1999)	
BEAM extinction calculator (Gonzalez et al. 2011, 2012)	http://mill.astro.puc.cl/BEAM/calculator.php
RJCE two-dimensional extinction maps	https://www.noao.edu/noao/staff/dnidever/rjce/extmaps/index.html
The Planck Dust Model Page	http://hyperstars.fr/mamd/planck_dust_model.html
Repository of a 3D extinction map of the northern Galactic plane based on IPHAS photometry (Sale 2012; Sale et al. 2014)	http://www.iphas.org/extinction/
Repository of photometric extinctions and distances (Chen et al. 2014)	http://162.105.156.249/site/Photometric-Extinctions-and-Distances/
A map of dust reddening to 4.5 kpc from Pan-STARRS1 (Schlafly et al. 2014)	http://faun.rc.fas.harvard.edu/eschlafly/2dmap/querymap.php
Spanish Virtual Observatory (VO) extinction map (Morales-Durán et al. 2015)	http://svo2.cab.inta-csic.es/theory/exmap/
A three-dimensional map of Milky Way dust (Green et al. 2015, 2018, 2019)	http://argonaut.skymaps.info
Dustmaps: A PYTHON interface for maps of interstellar dust (Green 2018)	https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/2EJ9TX or https://dustmaps.readthedocs.io/en/stable/index.html or https://github.com/greggreen/dustmaps
On Galactic density modelling in the presence of dust extinction (Bovy et al. 2016)	https://github.com/jobovy/mwdust
A new, large-scale map of interstellar reddening derived from H I emission (Lenz et al. 2017)	https://github.com/daniellenz/ebv_tools
Structuring by Inversion the Local Interstellar Medium (Lallement et al. 2014; Capitanio et al. 2017)	http://stilism.obspm.fr/
Gaia/2MASS: 3D dust extinction map (Lallement et al. 2019)	https://astro.acri-st.fr/gaia_dev/about/
Dust in three dimensions in the Galactic plane (Hanson et al. 2016)	http://www.rhanson.de/gpdust/
STARHORSE: a Bayesian tool for determining stellar masses, ages, distances, and extinctions for field stars (Queiroz et al. 2018)	http://www.linea.gov.br/020-data-center/aceso-a-dados-3/aceso-a-dados-2/#spectrophotometric_distances_and_extinction
Three-dimensional interstellar dust reddening maps of the Galactic plane (Chen et al. 2019)	http://paperdata.china-vo.org/diskce/cestar/table1.zip
Photo-astrometric distances, extinctions, and astrophysical parameters for Gaia-DR2 stars brighter than $G = 18$ (Anders et al. 2019)	https://gaia.aip.de/
A color-excess extinction map of the southern Galactic disk from the VVV and GLIMPSE surveys (Soto et al. 2019)	http://astro.userena.cl/ExtMapVVV/

These services are in general based on maps or models developed in different programming languages (which use specific file annotations, some of them large ASCII tables), with different user interfaces and input/output formats. The variety of interfaces and formats creates difficulties on the user side, in practice limiting the extinction maps and models used in scientific analysis. This in turn limits the ability to compare the effects of using different maps and models. It can also lead to the use of maps or models that may not be the most appropriate option for the study being made.

Here we present a web-based tool, GALEXTIN. The service has been created to overcome the problem above, by integrating dozens maps and models in a unique tool using one common simple user interface and output format.

The remainder of this paper is organized as follows. Section 2 presents an overview of the available interstellar extinction tools.

GALEXTIN, with the models/maps it provides, is presented in Section 3. A comparison among extinction estimates obtained with some models/maps is presented in Section 4. Section 5 presents the conclusions of this study and makes some final remarks.

2 A GENERAL OVERVIEW OF THE AVAILABLE INTERSTELLAR EXTINCTION TOOLS

The usage of an interstellar extinction map or model depends directly not only on its capabilities but also on its availability and feasibility. Table 1 details several available online services and repositories that provide the interstellar extinction of several models and maps. Most of them are based only on the estimates of interstellar extinction and reddening provided by their own authors. In the following section, we will briefly describe each of them and provide the respective links for the interested reader.

By the early 1980s, the maps of Burstein & Heiles (1978, 1982) were being distributed as ASCII files (the FORTRAN program outputs), or as contour maps in printed *The Astronomical Journal* papers. Further authoritative catalogues are those provided by Neckel & Klare (1980) and Fitzgerald (1968), which yield $E(B - V)$ towards a large number of stars.

On The NASA/IPAC Extragalactic Database (NED) webpage,¹ there is also a service called ‘Coordinate Transformation & Galactic Extinction Calculator’. This service provides not only transformations between different coordinates systems, but also interstellar extinction as provided by Burstein & Heiles (1978, 1982) and Schlegel et al. (1998), as well as its value using the calibration values provided by Schlafly & Finkbeiner (2011).

Arenou, Grenon & Gomez (1992) presented a 3D model that uses a sample of 215 000 stars contained in the INput CAlogue (INCA) database (Turon et al. 1991). On the extinction model page, users can choose from three methods: (i) extinction from V mag and $B - V$; (ii) extinction of V mag; and (iii) extinction as a function of ℓ , b and distance.

Since their publication, the models of Amôres & Lépine (2005) have been provided in IDL language or in FORTRAN² as The Model ALA. In a previous version of the GALEXTIN, they were also available for a private list of collaborators with a restricted list of maps and models (Amôres et al. 2012). The maps of Dobashi et al. (2005, 2013) are available through an interactive interface (for the link see Table 1), with an option to download a FITS file for a given region of the sky. Rowles & Froebrich (2009) launched an online interface, where they also provide maps for three resolutions as well as $E(B - V)$ for Schlegel et al. (1998) and Dobashi et al. (2005). Furthermore, it is feasible to retrieve extinctions for smaller-scaled maps, such as those produced by Lombardi, Alves & Lada (2006), Lombardi, Lada & Alves (2008) and Cambrésy (1999). It is also possible to obtain the extinction from the maps of Gonzalez et al. (2011, 2012) for a given pair of coordinates through an interactive interface (BEAM Calculator, see also Table 1), in which the users can choose from two different extinction laws – that of Cardelli, Clayton & Mathis (1989) or that of Nishiyama et al. (2009).

An online tool (see also Table 1) retrieves the data from Schlafly et al. (2014), which allows the user to obtain the $E(B - V)$ value for a given pair of ℓ , b . The user can also download the map, including instructions on how to read it using either IDL or PYTHON code. The data from Planck Collaboration et al. (2014b) can also be obtained in a single file (HFI.CompMap.ThermalDustModel_2048.R1.20.fits) available in the Planck Legacy Explanatory Supplement.³

Morales-Durán et al. (2015) developed a tool in the context of the Spanish Virtual Observatory that provides A_V , R_V and distance for a sample of approximately 200 000 stars. Their service provides a list of stars for a given pair of coordinates and search radius supplied by the user. Bovy et al. (2016), in the context of upcoming near-infrared spectroscopic surveys and *Gaia* (Gaia Collaboration et al. 2016), developed a likelihood-based phase-space inference framework for the Milky Way (MW). They also combined extinction models/maps (Marshall et al. 2006; Drimmel et al. 2003; Sale et al. 2014; Green et al. 2015, 2018) in a tool developed in PYTHON and available for download (see Table 1).

The maps of Hanson et al. (2016) cover an area of over 7000 square degrees towards the Galactic plane with a resolution of 6 arcmin and are displayed as a large table (see Table 1). Green (2018) elaborated a unified PYTHON interface, called *dustmaps* (Table 1), to retrieve interstellar extinction from several models and maps. This interface also includes the maps by Green et al. (2015, 2018, 2019), designated as Bayestar15, Bayestar17 and Bayestar19, respectively.

Santiago et al. (2016) derived a method to compute spectro-photometric distances applying a Bayesian approach and Sloan Extension for Galactic Understanding and Exploration (SEGUE) and The APO Galactic Evolution Experiment (APOGEE) data (Allende Prieto et al. 2008). Later, they developed (Queiroz et al. 2018) and applied their method (called STARHORSE) to compute distances and extinction using APOGEE, RAVE (Steinmetz et al. 2006), and the *Gaia*-ESO Survey (GES, Gilmore et al. 2012). Anders et al. (2019), using *Gaia*-DR2 combined with PS1, 2MASS, and ALLWISE, computed not only stellar parameters but also distances and extinction for 265 million stars brighter than $G=18$.

Lenz, Hensley & Doré (2017) presented a map of interstellar reddening based on H I column densities for 39 per cent of the sky with good accuracy in the low-density regime. The map provided by Lallement et al. (2019) covers distances up to 3 kpc and is available for use either through their tool (Table 1) or via download at CDS.⁴ In addition, the 3D extinction maps provided by Lallement et al. (2014) and Capitanio et al. (2017) are also available from an online interface (Table 1).

Soto et al. (2019) established a service that provides extinction for one pair of coordinates (see Table 1). It is also possible to download maps and to use an IDL script to retrieve extinction values at specified coordinates. The map of Babusiaux et al. (2020) is available at the following link.⁵ The map of Guo et al. (2021) is available at this link,⁶ with an example of PYTHON code to access the interstellar extinction from a 3D position.

3 GALEXTIN

GALEXTIN can deliver either the interstellar extinction or reddening towards any given position in our Galaxy given the coordinates and distance, or an integrated extinction along a line of sight. In the latter case, more useful for extragalactic studies, only coordinates need to be provided (Burstein & Heiles 1978, 1982; Schlegel et al. 1998; Schlafly et al. 2014; HI4PI Collaboration et al. 2016; Lenz et al. 2017). The user must provide either the Galactic or equatorial coordinates (ℓ , b) of a single object (direction) or a list of coordinates (including distance) in an ASCII file separated by spaces. Presently, only lists with up to 1000 directions and for one model/map per run are accepted.

The GALEXTIN front-end is designed as a web application, with a network background composed of HTML tags, PHP scripts and access to a MYSQL database. We wrote the majority of the programs in IDL, with minor subroutines in PYTHON, FORTRAN and C.

GALEXTIN works with two layers. The first one is a client that provides a web form to be filled out by the user, for example data such as coordinates and distance for the 3D extinction. Alternatively, the user can insert a list of coordinates (Galactic or equatorial) with

¹https://ned.ipac.caltech.edu/extinction_calculator

²http://galexin.org/amores_lepine.php

³https://wiki.cosmos.esa.int/planckpla/index.php/CMB_and_astrophysical_component_maps#The_5Bmath.5DE.28B-V.29.5B.2Fmath.5D_map_for_ext_ra-galactic_studies

⁴<https://cdsarc.unistra.fr/viz-bin/ReadMe/J/A+A/625/A135?format=html&ex=true>

⁵<http://cdsarc.u-strasbg.fr/viz-bin/cat/J/A+A/641/A79>

⁶<https://nadc.china-vo.org/article/20200722160959?id=101032>

distances. It is also necessary to select the coordinate system and the desired model/map.

The PHP program, embedded in the HTML code, accesses an SQL table to attribute a number to the process, namely a unique identification for each run of GALEXTIN, which is also used to assign and manipulate input and output file names. Once PHP receives a process number and the information passed through HTML, it calls an IDL program that manages the extinction computation. It verifies the number of input lines. Its primary task consists of calling the routines that compute the interstellar extinction for each chosen model/map.

In the final step, the routine returns the extinction estimates to the main program. The output is displayed in web form if a single direction was given, or written to a file if a file with coordinates was provided. For both Galactic and equatorial coordinates, the values must be given in decimal degrees.

3.1 Models available in GALEXTIN

Two models for interstellar extinction determination in the Galaxy, as presented by Amôres & Lépine (2005), are available: the Axysimetric Model (Model A) and the Spiral Model (Model S), as well as one model (Model A2) described in Amôres & Lépine (2007) that slightly improves the Axysimetric Model outside the Galactic plane. The three models are written in IDL.

For Burstein & Heiles (1978, 1982), we used the `bhrdfort.pro` routine that was written by D. Schlegel based on Michael Strauss' FORTRAN data files that return as output $4E(B - V)$. When using those values for $E(B - V)$, attention should be paid to the zero-points (Burstein 2003). As pointed out in the documentation of the routine, valid data has the output > -0.22 .

The most used extinction estimates in the literature are those of Schlegel et al. (1998), which are also available in GALEXTIN. We used the function `dustgetval.pro` with interpolation. GALEXTIN provides not only the $E(B - V)_{\text{SFD}}$ but also the A_V for Landolt V ($R_V = 3.1$) by using the Fitzpatrick & Massa (2005) reddening law as presented by Schlafly & Finkbeiner (2011) (table 6). In the case of other bandpasses, it is only necessary to multiply $E(B - V)_{\text{SFD}}$ by the value provided in this table. For both Burstein & Heiles (1978, 1982) and Schlegel et al. (1998), we used the FITS, routines and data files provided on their website.⁷

The 3D Model of Drimmel et al. (2003) provides the extinction in the V band. We obtained the FORTRAN version provided on the author's webpage.⁸

The extinctions provided by Marshall et al. (2006),⁹ Chen et al. (2013),¹⁰ Chen et al. (2014) and Sale et al. (2014) are all given in tables with coordinate information followed by ranges of distance, extinction and the errors. The links to obtain the extinction for Chen et al. (2014) and Sale et al. (2014) are provided in Table 1.

To better manipulate those auxiliary files, we split each one of them into two FITS files, the first one with the coordinates, and the second with a single structure containing extinction, distance and the error for a given distance, as well as the number of the field that is linked with the coordinates file.

For instance, the Marshall et al. (2006) original file has a size of 52 MB. It is split into two files, one with the coordinates and the other with interstellar extinction and distance estimates. The sizes of the split files are approximately 0.5 and 8.3 MB. The elapsed time to read those FITS files is almost 1 per cent of the time to read the large Marshall et al. (2006) table. One important characteristic of GALEXTIN is that for each process, the large files as well as the main data in the models are loaded only once in the memory.

From the coordinates (ℓ , b) for a given extinction, GALEXTIN obtains the nearest position, allowing a maximum distance of $0.^\circ5$. In the output, not only the input but also the obtained (ℓ , b) and distance are provided, which informs the user how far from the original direction the output is.

As the intervals between the points in the extinction data from Marshall et al. (2006) and Chen et al. (2013) could be large (for instance, the distance between the last two points is 1.0 kpc), we performed a linear interpolation between the points to provide a finer estimate of the interstellar extinction and the error, rather than using the estimate given by the authors. The interval for the interpolation in the distance is equal to 10 and 50 pc for Marshall et al. (2006) and Chen et al. (2013), respectively. Regarding the map of Chen et al. (2013), the colour excesses for both $E(J - K_s)$ and $E(H - K_s)$ are provided.

In the case of 3D data obtained from Chen et al. (2014), we do not interpolate the data because the resolution of their map is 0.15 kpc. In this case, for a given pair of coordinates, we consider the point nearest to the input direction. The estimates of Chen et al. (2014) reach distances up to 4.35 kpc, and the authors present extinction in A_r that can be converted to A_V using the linear relationship $A_V = 1.172 A_r$ (Yuan, Liu & Xiang 2013).

For Sale et al. (2014), despite the resolution in the distance being equal to 0.10 kpc, we still interpolate it with intervals of 0.05 kpc. We applied the interpolation to compare it with the data obtained (see Section 3.2) from CDS-Vizier, available for distances equal to 1, 3 and 10 kpc. As the original map's first extinction value is for a distance equal to 0.05 kpc (with steps of 0.10 kpc), we only obtain those distance values by interpolating.

The Planck Dust Model for All-Sky is available in GALEXTIN for $E(B - V)$ for extragalactic studies. It is essential to note that this value is integrated along with all the MW line of sight. We also provide the H I column density (N_{HI} in cm^{-2}) obtained from the observations of HI4PI Collaboration et al. (2016) available in FITS format at the CDS.¹¹

The maps presented in Sale et al. (2014) cover the Galactic plane towards the northern sky with distances up to 15.0 kpc. They provide the monochromatic extinction (A_0) at 5495 Å. As pointed out in Sale et al. (2014), $A_0 = 1.003 A_V$.

We also provide the reddening given by *dustmaps* from Green et al. (2015, 2018, 2019) using the mode equal to best for Bayestar15, Bayestar17 and Bayestar19. Programs and data from *dustmaps* are only used by GALEXTIN for this purpose. The output values are given in specific units for each one of them, namely Bayestar15, Bayestar17 and Bayestar19, see Green et al. (2018, 2019). To convert them to either $E(B - V)$ or an extinction in any passband, see those papers and the links given in footnotes¹² and¹³.

The colour-excess map by VVV (Soto et al. 2019) is also available within GALEXTIN, with A_{K_s} values and their standard deviations. The

⁷<https://doi.org/10.7910/DVN/EWCNL5>

⁸<ftp://ftp.oato.inaf.it/astrometria/extinction>

⁹<https://cdsarc.unistra.fr/viz-bin/ReadMe/J/A+A/453/635?format=html&ex=true>

¹⁰<https://cdsarc.unistra.fr/viz-bin/ReadMe/J/A+A/550/A42?format=html&ex=true>

¹¹<ftp://cdsarc.u-strasbg.fr/pub/cats/J/A+A/594/A116>

¹²<http://argonaut.skymaps.info/usage#units>

¹³<https://dustmaps.readthedocs.io/en/latest/modules.html>

maps of interstellar reddening by Lenz et al. (2017) are available in GALEXTIN, with values provided in $E(B - V)$.

Chen et al. (2019) provided, in a single file, the colour excesses as a function of the Galactic longitude, latitude and distances, ranging from 0.2 to 6.0 kpc with a step of 0.2 kpc. Within GALEXTIN, we have split the extinction data by Chen et al. (2019) into two files. One file has the Galactic coordinates and maximum distance for each pair of coordinates. The second file has a key to assign the distance and the extinction in A_G and its error estimate. We used the expressions provided by the authors to compute $A_G = E(G - K_S) + 1.987 E(H - K_S)$. The error was estimated applying $A_G = 1.987 E(H - K_S)_{\text{error}}$. GALEXTIN provides the extinction of the point nearest to the input distance.

Fig. 1 shows the values obtained using GALEXTIN and those by other authors for some lines of sight. As can be seen, there is full agreement between the GALEXTIN values and the results provided by the other authors.

3.2 Validation

The maps and models currently available in GALEXTIN were validated in the sense that results obtained with GALEXTIN are fully reproduced, which can be seen by comparison with the original data provided by the authors, with *dustmaps*, and in other ways, as described below. The fact that in the context of GALEXTIN only the code available for the maps of Bayestar15, Bayestar17 and Bayestar19 is used from *dustmaps* reinforces the robustness of our results. On the GALEXTIN page, we also provide detailed information for all comparisons and files used.

It is essential to verify the reproducibility and consistency of the results. To do so, we performed some comparisons based on the model/map coverage. For instance, for the maps Burstein & Heiles (1978, 1982), we compared the results obtained using GALEXTIN and the values obtained by *dustmaps* towards a sample of 378 elliptical galaxies as published by Burstein (2003).

For the map of Schlegel et al. (1998), we used a grid of points based on the Hierarchical Triangular Mesh (HTM) level 6 (Kunszt, Szalay & Thakar 2001) to obtain the pairs of coordinates distributed over All-Sky, 32 768 points in total. In this context, we compared the results obtained by GALEXTIN and also the values obtained using *dustmaps*.

We used the same grid with added distance, ranging randomly from 0 to 30 kpc, for the models of Amôres & Lépine (2005, 2007), except for the Model S, for which we reduced the tests for the inner Galaxy ($|\ell| \leq 100.^\circ$) to $|b| \leq 10.^\circ$, totalling 12 598 points. For those models, we used the same versions as provided on their webpage and compared the results obtained using GALEXTIN with the values obtained on a local machine.

Regarding the model of Drimmel et al. (2003), there is a file on its webpage (see above) with interstellar extinction for eight directions, and we compared the values obtained using GALEXTIN not only for those directions but also for a grid with 2000 pairs of coordinates (see below) using GALEXTIN and the author's code on a local machine.

For the All-Sky Planck Dust Model, we compared the values obtained with GALEXTIN for $E(B - V)$, but we also built from the HTM level 6 another grid of points containing 2000 pairs of coordinates distributed at random for All-Sky, comparing the results from GALEXTIN with the values obtained using the *dustmaps* interface.

For Marshall et al. (2006), Chen et al. (2013) and Sale et al. (2014), we downloaded the data from the CDS-Vizier interface application, considering a regular interval of ℓ , b and distance. An important

point to note is that the original values for these extinction estimates were also obtained from CDS (in a single file), but in this case we downloaded the entire full file and also used another program to read the files in order to avoid any bias. For Chen et al. (2013), we performed the validation with both $E(J - K_S)$ and $E(H - K_S)$.

To validate these three maps, we compiled a catalogue of 7190, 711 and 1050 pairs of coordinates and distance. For Chen et al. (2014), we obtained points randomly from the data file provided by the authors using a procedure different from the one used by GALEXTIN to fetch its data.

To check the results provided by Bayestar (Green et al. 2015, 2018, 2019), we ran GALEXTIN for some directions as described in the documentation of *dustmaps* as well as comparing the values using GALEXTIN with those obtained running *bayestar* on the local machine for the same file with 2000 pairs of coordinates.

To verify the HI4PI collaboration data, we also used the CDS-Vizier interface application, fetching the H I column density for Galactic longitudes ranging from $0.^\circ$ to $355.^\circ$ (steps of $20.^\circ$) and Galactic latitudes from $-85.^\circ$ to $+85.^\circ$ (steps of $10.^\circ$), totalling 660 pairs of coordinates.

We validated the map by Lenz et al. (2017) in two ways. In the first approach, we considered four pairs of Galactic longitude and latitude and $E(B - V)$ as provided by the authors on their website (see Table 1). Later, we considered a list of 2000 pairs of coordinates running in GALEXTIN as well as with *dustmaps*. For the record, there are 754 pair of coordinates with a valid $E(B - V)$ estimate towards the list of 2000 pairs of coordinates mentioned above.

Using the Chen et al. (2019) original reddening file, we produced a list of 1000 directions with Galactic coordinates and then compared this with the GALEXTIN results. In all comparisons, we found the relative difference between the results from GALEXTIN and those provided in the comparison files to be equal to zero (see Table 2 for the rms). It is worth noticing a minimal difference of 2.951×10^{-3} in the rms in comparison to the A_0 value provided by Sale et al. (2014) between CDS and our values for the three ranges of distances returned by CDS at 1, 3 and 10 kpc. This small difference comes from the fact that we interpolated the values of extinction along the line of sight. We also verified the values obtained by GALEXTIN for Sale et al. (2014) for a list with 5508 points, containing 612 pairs of (ℓ, b) for nine distances, obtained aleatorily directly from the IPHAS: 3D extinction map.¹⁴ We notice that the rms (5.042×10^{-5}) in this comparison is lower than the one obtained in the previous comparison (see Table 2).

To validate the map of Soto et al. (2019), we elaborated a grid with 555 points covering its whole region, at every 0.5° for both Galactic longitude and latitude. The rms is equal to 0.0003.

For the record, Table 2 also shows the elapsed time and the rms for each model/map taking into account a given number of lines of sight. As can be seen, even for a large number of lines of sight, the computation time is low. We performed these simulations running GALEXTIN only on our server.

4 RESULTS

In addition to the sanity check reported in the previous section, we also expanded our comparison of the results obtained with GALEXTIN and other authors in the same way as performed by Bovy et al. (2016) in their fig. 5. The authors compare, in this

¹⁴<http://www.iphas.org/data/extinction/Amap.tar.gz>

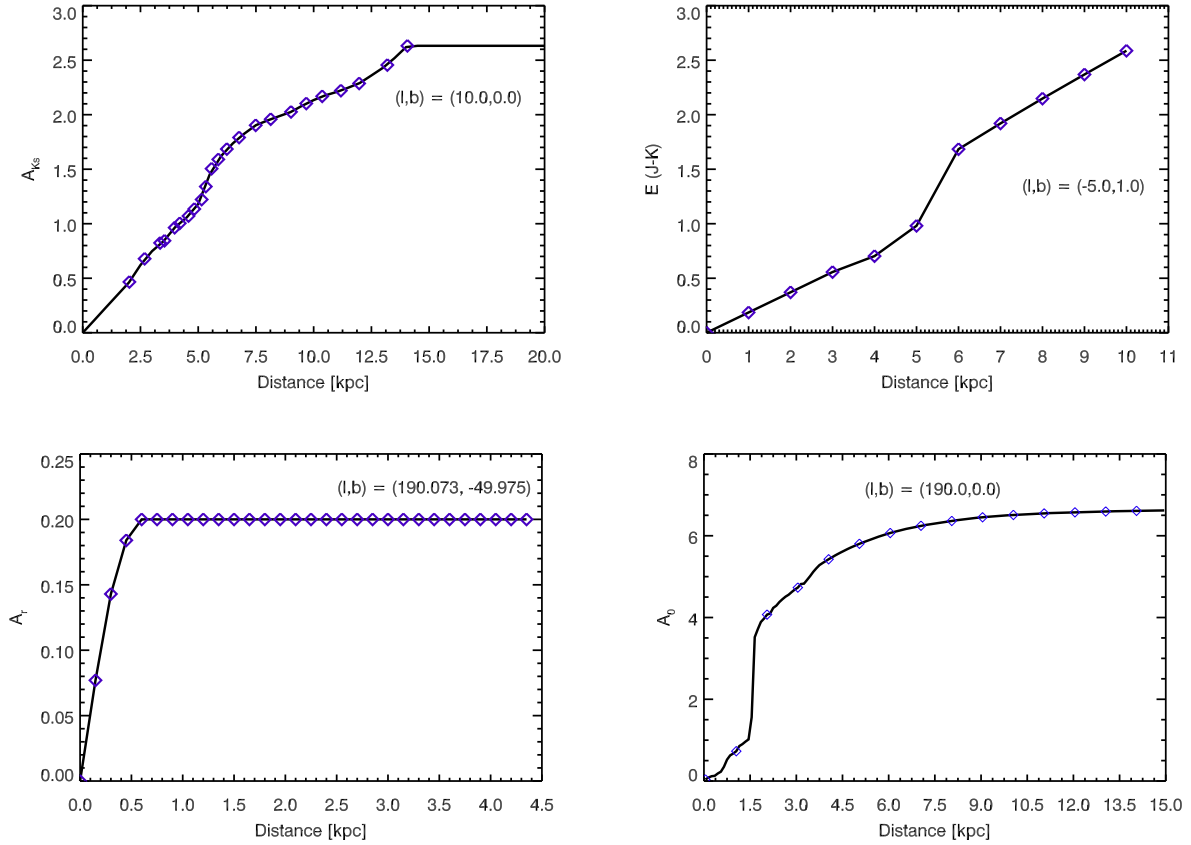


Figure 1. Extinction versus distance as provided by some authors (points): upper left-hand panel, Marshall et al. (2006); upper right-hand panel, Chen et al. (2013); lower left-hand panel, Chen et al. (2014); lower right-hand panel, Sale et al. (2014), and as obtained using GALEXTIN (lines). The coordinates are indicated at the top of each panel.

Table 2. Models/maps available in GALEXTIN with the computation time, for each one in our server for different samples of line of sight (los).

Model/map	Time	Number of los	Reddening/extinction	rms
Burstein & Heiles (1978), Burstein & Heiles (1982)	2 s	378	$E(B - V)$	2.770×10^{-3}
Schlegel et al. (1998)	1 min	32 768	$E(B - V)_{\text{SFD}}$ and V -Landolt (Schlafly & Finkbeiner 2011)	1.370×10^{-4}
Drimmel et al. (2003)	1 min	2000	A_V	1.100×10^{-7}
Amôres & Lépine (2005) – ALA	22 s	32 768	A_V	0.000000
Amôres & Lépine (2005) – ALS	7 min	12 598	A_V	1.992×10^{-5}
Amôres & Lépine (2005) – ALNF	22 s	32 768	A_V	7.813×10^{-6}
Amôres & Lépine (2007) – AL2	41 s	32 768	A_V	1.104×10^{-5}
Marshall et al. (2006)	4 min	7190	A_{K_s}	0.000000
Chen et al. (2013)	5 s	711	$E(J - K_s)$ and $E(H - K_s)$	0.000000 for both
Chen et al. (2014)	70 s	711	A_V	0.000000
Sale et al. (2014)	30 s	1050	A_0 at 5495Å	2.951×10^{-3} and 5.042×10^{-5}
Schlafly et al. (2014)	6 s	100	$E(B - V)$	0.000000
Planck Collaboration et al. (2014b)	10 s	2000	$E(B - V)$	0.000000
HI4PI Collaboration et al. (2016)	4 min	660	N_{HI} in cm^{-2}	9.110×10^{-3}
Green et al. (2015)	80 s	2000	Bayestar15	0.000000
Green et al. (2018)	160 s	2000	Bayestar17	0.000000
Green et al. (2019)	130 s	2000	Bayestar19	0.000000
Lenz et al. (2017)	40 s	2000	$E(B - V)$	2.834×10^{-6}
Soto et al. (2019)	12 s	555	A_{K_s}	0.000000
Chen et al. (2019)	5 min	1000	A_G	2.099×10^{-4}

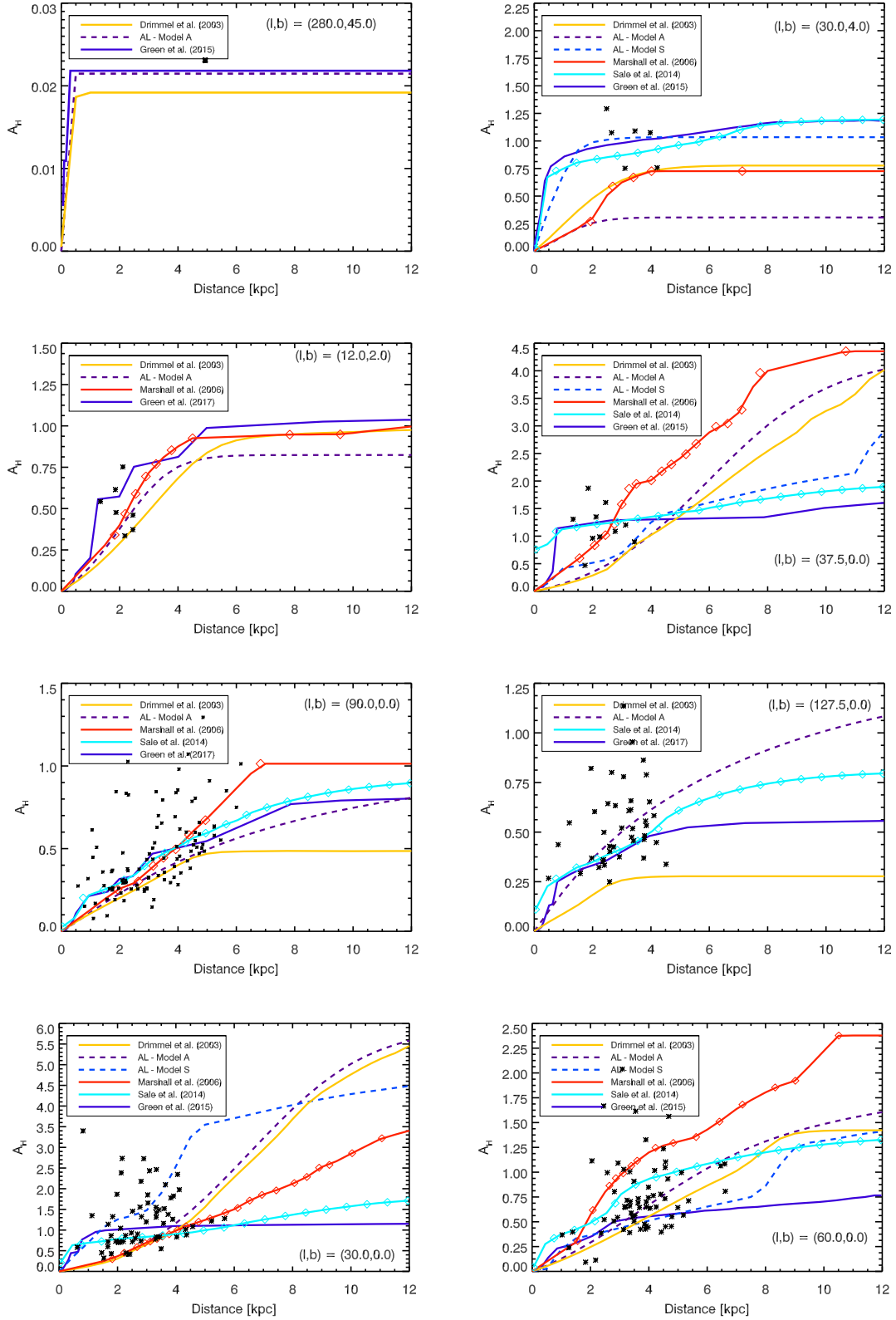


Figure 2. Extinction versus distance for some models as detailed in the legends. The asterisks are stars in the APOGEE-RC Catalogue located within 4 square degrees of the centre of the coordinates presented in each panel.

figure, the values of A_H provided by several authors as a function of distance.

In order to compare the estimates of GALEXTIN, we have produced a similar figure, also adding the estimations of the models of Amôres & Lépine (2005). Fig. 2 shows this comparison. For most directions we considered the Axis and Spiral models of Amôres & Lépine (2005), except for directions in which the contribution of the spiral arms either is not expected or is negligible.

In contrast to Bovy et al. (2016), who considered an average extinction within a radius centred on the coordinates, we only considered the extinction towards a given direction (top in the panels of Fig. 2). Similar to Bovy et al. (2016), we also obtained the stars nearest to the centre of the coordinates; in our case, stars from the APOGEE-RC Catalogue¹⁵ within a box of size $2^\circ \times 2^\circ$. To convert values to A_H , we used the values provided by Rieke & Lebofsky (1985).

In general, there is good agreement between the models in all directions, and at least for some distance ranges. The differences can be attributed to the characteristics of each model, their coverage, resolution, and the tracers used to elaborate them. We can see an interesting feature in the Amôres & Lépine (2005) Spiral model, which is the fact that extinction increases by discrete steps passing through spiral arms. Furthermore, the model is in good agreement with the extinction of the APOGEE-RC Catalogue. We used the Amôres & Lépine (2005) – Model A (ALA), as the first option to retrieve using the fine-tuning, in the direction of $(\ell, b) = (127.^\circ 5, 0.^\circ 0)$; however, GALEXTIN provides extinction values also considering a no fine-tuning option (ALNF).

5 CONCLUSION

We have developed an online tool that supports interstellar extinction estimates for 20 models/maps available in the literature. The user only needs to supply a pair of coordinates and possibly the distance, or, alternatively, a file with multiple sky coordinates. We validated our tool by comparing the results of GALEXTIN with the results obtained with the original software of the models, *dustmaps*, as well as with the values obtained using VizieR–CDS in the case of some maps. We plan to include new models/maps in GALEXTIN regularly. In the future, we also plan to have VO accessibility and interfaces and use VOTable as a default data format.

By providing a uniform web-based interface and output format, GALEXTIN allows users to explore, compare and otherwise use several extinction models and maps, without having to install numerous programs or even download large tables. We wish to emphasize that GALEXTIN builds on the work done by other authors who have developed the underlying tools and maps, and that there are several other excellent extinction maps and models not currently offered in GALEXTIN. To clearly acknowledge some of those works, brief descriptions, as well as links to their web pages, are presented in Table 1, and will be regularly updated on the GALEXTIN page.

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DATA AVAILABILITY

The data underlying this article were accessed from <http://www.galextin.org>. The derived data generated in this research will be shared on reasonable request to the corresponding author.

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¹⁵http://www.sdss.org/dr14/data_access/value-added-catalogs/?vac_id=apogee-red-clump-rc-catalog

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