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THE HABITABLE ZONE GALLERY

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ABSTRACT

The Habitable Zone Gallery (www.hzgallery.org) is a new service to the exoplanet community which provides Habitable Zone (HZ) information for each of the exoplanetary systems with known planetary orbital parameters. The service includes a sortable table with information on the percentage of orbital phase spent within the HZ, planetary effective temperatures, and other basic planetary properties. In addition to the table, we also plot the period and eccentricity of the planets with respect to their time spent in the HZ. The service includes a gallery of known systems which plot the orbits and the location of the HZ with respect to those orbits. Also provided are animations which aid in orbit visualization and provide the changing effective temperature for those planets in eccentric orbits. Here we describe the science motivation, the under-lying calculations, and the structure of the web site.

Subject headings: astrobiology – astronomical databases: miscellaneous – planetary systems

1. INTRODUCTION

The field of exoplanets has undergone enormous diversification over the past 20 years. The reasons for this include (but are not limited to): new detection techniques, longer period baseline, smaller mass/radii sensitivity, and atmosphere detection and modeling. As a result of these developments, we are able to accurately characterize the orbits of exoplanets and infer properties of their atmospheres surface conditions. The sensitivity of radial velocity and transit surveys to planets at longer periods is fundamentally limited by the survey duration. Many of the radial velocity surveys are now pushing this detection threshold beyond orbital periods of 10 years and with upgraded instruments are sensitive to masses only a few times that of the Earth. This means that many of the known planets pass through or remain in the Habitable Zone (HZ) of their parent stars, some of these with potentially rocky surfaces or terrestrial sized moons.

Keeping an accurate and exhaustive list of the known exoplanets is an increasingly difficult tasks, but there exist numerous electronic sources of information regarding exoplanets and their host stars. Notable examples are the Extrasolar Planets Encyclopeadia[1], the NASA Exoplanet Archive[2], and the Exoplanet Data Explorer (EDE)[3]. The EDE stores information only for those planets which have complete orbital solutions, typically from a Keplerian fit to radial velocity data acquired on those targets, and thus is very useful for this study.

The Habitable Zone Gallery (HZG) is a unique service which tracks the orbits of exoplanets in relation to the HZ of their host stars. This includes calculation of planetary temperatures, percentage of the orbital phase spent within the HZ, and figures/movies which depict planetary orbits with respect to the HZ. This allows for easy reference of interesting systems in this context and target selection for future investigations. This is also a useful tool for describing exoplanets in Education & Public Outreach (EPO) efforts. Here we detail the methodology used to perform the necessary calculations for generating the information on the HZG and the figures presented throughout.

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[1] http://exoplanet.eu/
[2] http://exoplanetarchive.ipac.caltech.edu/
[3] http://exoplanets.org/

2. SCIENCE MOTIVATION

The HZ is a key concept in our understanding of the conditions under which basic life can form and survive. On our own planet we find extreme conditions under which organisms are able to not only sustain metabolic processes, but thrive and grow. Thus this understanding informs our precepts on how life formed in our own Solar System and also the possibility of similar processes in exoplanetary systems. Although the concept of the HZ has been in the literature for some time, it is only within the past 20 years that complex atmospheric models have been developed to allow a rigorous examination of its nature. In particular, the response of different atmospheres to varying amounts of stellar flux allows the determination of HZ boundaries for known exoplanetary systems. The pioneering work on this was carried out by Kasting et al. (1993) with subsequent papers producing more analytical expressions for a variety of main sequence stars (Jones & Sleep 2010; Kasting et al. 1993; Selsis et al. 2007; Underwood et al. 2003).

Exoplanet survey sensitivity is spreading in various directions; to lower masses, to longer periods, and to later and earlier spectral types. This broadening of the field opens up new areas to explore in terms of the Habitable Zones of these configurations. The topic of the HZ has become even more relevant in the wake of the results from the Kepler mission. Approaches to investigating the HZ of Kepler stars has been suggested by Kaltenegger & Sasselov (2011) and many of the candidates released are within the HZ of their host stars (Borucki et al. 2011a,b). The announcements of the Kepler-20 system (Fressin et al. 2012; Gautier et al. 2012) and Kepler-22b (Borucki et al. 2011c) mark the crossing of a significant threshold in narrowing down the search for an Earth mass/radius planet which lies within the HZ of a solar-type star. Although these results inform us greatly as to the frequency of habitable terrestrial planets, the relative faintness of the Kepler sample makes more detailed follow-up difficult.

A new area of habitability being explored is that of terrestrial moons of giant exoplanets which lie within the HZ of their parent stars. This has been discussed in the context of the Kepler mission quite thoroughly (Kaltenegger 2010; Kipping et al. 2009). Based upon the statistics from our own Solar System, it is natural to expect that many of the planets discovered via the radial velocity method do indeed harbor moons of various size and composition. For the giant planets themselves, great progress is being made towards understanding the effective temperatures of these bodies depending upon their albedos, thermal response, and atmospheric circulation (Kane & Gelino 2010, 2011). Likewise for the moons in these systems, the habitability prospects will depend largely upon the conditions under which the primary planet is subjected to.

The science motivation and use cases for the HZG can thus be summarized as follows. 1. To provide an interactive method by which users may visualize the orbits and Habitable Zones of known exoplanetary orbits. 2. To provide tools, graphics, and movies which can be easily imported into presentations to facilitate communication of these concepts in both public and scientific contexts. 3. To provide an interactive table tool which allows users to sort for planets which spend substantial amounts of time within the HZ and thus aid in target selection for further studies. 4. Ultimately, and of particular interest to the authors, one would like to investigate the habitability of exoplanets and exomoons whose total energy budget varies with a cyclic nature, usually caused by orbital eccentricity and consequently variable stellar flux.

3. HABITABLE ZONE AND ORBITS

In order for the HZG to function, it requires the ability to calculate HZ parameters in a non-interactive fashion. Here we describe the stellar and planetary information required and the subsequent calculations performed.

3.1. *Necessary Information*

The HZG uses as input a variety of stellar and planetary parameters to carry out the necessary calculations. The data for the planets listed in the HZG are primarily extracted from the EDE, described in more detail by Wright et al. (2011). The full list of required parameters is shown in Table 1. As one might expect, not all required parameters are available in all cases. In order to provide as complete a list as possible, the HZG code attempts to fill in the data gaps using published material on known stellar and planetary properties. These are described in detail in Section 3.2.

3.2. *Assumptions and Missing Values*

The planetary temperature calculations are based upon parameters which aren't available in all cases, and thus assumptions are occasionally made. The largest sources of uncertainties in the calculations are caused by the generally unknown radii of both the host star and the planet. In cases where the radius of the star is not available from other sources, we estimate the radius from the derived values of the surface gravity $\log g$ using the relation

$$\log g = \log\left(\frac{M_\star}{M_\odot}\right) - 2\log\left(\frac{R_\star}{R_\odot}\right) + \log g_\odot \quad (1)$$

where $\log g_\odot = 4.4374$ (Smalley 2005).

For non-transiting planets, a planetary radius measurement is invariably not available. The mass-radius relationship of exoplanets has been extensively studied, particularly with regards to composition models such as that described by Swift et al. (2012). To produce an estimate of planetary radii, we fit a simple model to the available data for confirmed transiting planets extracted using the EDE. The data are current as of 3rd January 2012 and include 135 planets.

These data are plotted in Figure 1. For masses greater than ~ 0.3 Jupiter masses (M_J) the radii generally follow a linear model which approximates to 1 M_J. This is true for masses well into the brown dwarf regime (see for example for isochrone models of Baraffe et al. (2003)). However, there is a significant divergence from a linear model for masses less than 0.3 M_J. To account for this we fit a power law to those data to obtain a better first order approximation of the radii of those objects. The overall

TABLE 1
Required input parameters

Parameter	Symbol
Stellar	
Mass	$M_\star$
Radius	$R_\star$
Effective temperature	$T_{\rm eff}$
Surface gravity	$\log g$
Planetary	
Mass	M_p
Radius	R_p
Period	P
Semi-major axis	a
Eccentricity	e
Periastron argument	ω

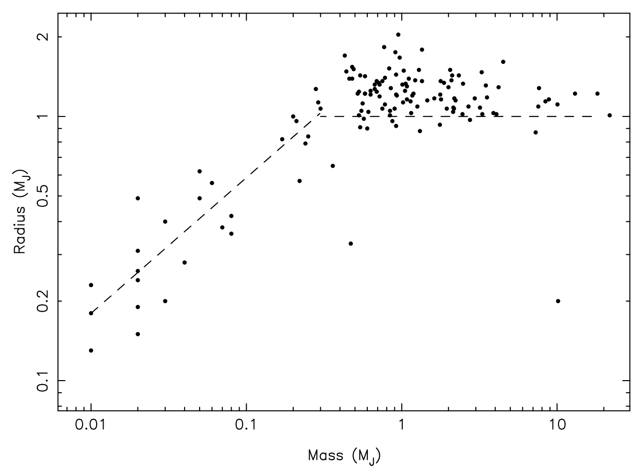

Fig. 1.— The mass and radius of known transiting planets. The dashed line indicates the model which the HZG uses to produce an approximation of the radius for non-transiting planets, where a power law is used for $M_p < 0.3\ M_J$ and a constant value of 1.0 M_J is implemented for $M_p > 0.3$.

model used is shown in Figure 1 as a dashed line. These radii may be used to calculate predicted planetary flux values at both infra-red and optical wavelengths and also to estimate planetary densities for aid in further characterization scenarios. This assumes that the actual mass of the planets is close to the minimum mass deduced from the Keplerian orbital solutions. It is also worth noting that this sample is highly biased towards short-period orbits, typical of transiting planets, where the planetary radii can be inflated due to increased irradiation and tidal effects. Consequently, the median period of the plotted sample is relative low (3.41 days).

A crucial parameter for estimating the planetary effective temperatures is the planetary albedo, specifically at infrared wavelengths. This is frequently assumed to be zero, as is the case here, which then presupposes that the planet absorbs all incident radiation and behaves as a blackbody. With the possible exception of cases where internal and atmospheric heating contributes to this temperature, the calculated temperature is likely to be overestimated.

Finally, many of the short-period planet discoveries (particularly those discovered using the transit method) assume a circular orbit and do not provide measurements of the eccentricity of argument of periastron. In those cases we assume $e = 0.0$ and $\omega = 90°$ which is equivalent to fixing the time of periastron passage to the predicted time of mid-transit.

3.3. *Fundamental Calculations*

For each of the planets which meet the minimum parameter requirements described above, we perform the following calculations. The first step is to calculate the extent of the HZ based upon the properties of the host star. In order to do this we require the luminosity of the host star, which is approximated as

$$L_\star = 4\pi R_\star^2 \sigma T_{\mathrm{eff}}^4 \tag{2}$$

where σ is the Stefan-Boltzmann constant.

Using the boundary conditions of runaway greenhouse and maximum greenhouse effects at the inner and outer edges of the HZ respectively (Underwood et al. 2003), the stellar flux at these boundaries are given by

$$S_{\mathrm{inner}} = 4.190 \times 10^{-8} T_{\mathrm{eff}}^2 - 2.139 \times 10^{-4} T_{\mathrm{eff}} + 1.268$$
$$S_{\mathrm{outer}} = 6.190 \times 10^{-9} T_{\mathrm{eff}}^2 - 1.319 \times 10^{-5} T_{\mathrm{eff}} + 0.2341$$

The inner and outer edgers of the HZ are then derived from the following

$$r_{\mathrm{inner}} = \sqrt{L_\star / S_{\mathrm{inner}}}$$
$$r_{\mathrm{outer}} = \sqrt{L_\star / S_{\mathrm{outer}}}$$

where the radii are in units of AU and the stellar luminosities are in solar units.

The next calculation performed is that of the planetary equilibrium effective temperature. Without any direct knowledge of the surface conditions or atmosphere of the planet, this calculation requires numerous assumptions which can be used to estimate a range of temperature values. One such assumption is that of the heat redistribution efficiency of the atmosphere which depends upon zonal wind speeds. If the atmosphere is 100% efficient at redistributing heat ("well-mixed" model), the planetary equilibrium effective temperature is given by

$$T_p = \left(\frac{L_\star (1 - A)}{16 \pi \sigma r^2} \right)^{\frac{1}{4}} \tag{3}$$

where A is the spherical (Bond) albedo and r is the star–planet separation. If the atmosphere is completely inefficient with respect to heat redistribution then the effective temperature is

$$T_p = \left(\frac{L_\star (1 - A)}{8 \pi \sigma r^2} \right)^{\frac{1}{4}} \tag{4}$$

which results in a hot dayside for the planet. The HZG provides the calculated values for both the periastron and apastron locations of the orbit. In the case of the movies (see Section 4.3) the well-mixed temperatures are calculated at each location of the orbit where a Keplerian solution is evaluated.

The final calculation is that of the Keplerian orbit. The true anomaly, f, is the angle between the position at periastron and the current position in the orbit measured at the focus of the ellipse. The mean anomaly is defined as

$$M = \frac{2\pi}{P}(t - t_p) \tag{5}$$

and is hence the fraction of the orbital period that has elapsed since the last passage at periastron, t_p. From the mean anomaly we can calculate the eccentric anomaly, E, which is the angle between the position at periastron and the current position in the orbit, projected onto the ellipse's circumscribing circle perpendicularly to the major axis, measured at the centre of the ellipse. These two quantities are related via Kepler's equation

$$M = E - e \sin E \tag{6}$$

which we solve via the Newton-Raphson method and has the solution

$$E = \frac{M - e(E \cos E - \sin E)}{1 - e \cos E} \tag{7}$$

This yields the value of E and hence the value of f

$$\cos f = \frac{\cos E - e}{1 - e \cos E} \tag{8}$$

The star–planet separation for eccentric planets has the following form

$$r = \frac{a(1 - e^2)}{1 + e \cos f} \tag{9}$$

Thus, we deduce from Equations 3 and 4 that the eccentricity of a planetary orbit introduces a time dependency to the effective temperature of the planet.

3.4. *A Note on "Habitability"*

The question arises as to whether those planets which are found to lie within their host stars HZ are indeed habitable. This is unknown since there are a variety of planetary properties that contribute towards habitability in addition to the flux received from the host star (Schulze-Makuch et al. 2011). For example, many of the planets described here are giant planets which may not even have a rocky surface. Moons of those systems may have conditions more suitable to sustaining life however (Kane & Gelino 2010). The view of what makes a planet habitable has an inevitable anthropic selection effect which contributes to our selection of preferred targets (Waltham 2011). The survival of extremophiles in orbits which are not consistently within the HZ are also poorly understood since we have no precedents for those conditions within our own system (Kane & Gelino 2012). The variety of factors which thus influence the sustainability of life must be accounted for when considering if a planet within the HZ is truely a candidate for potentially hosting life.

4. WEB SITE STRUCTURE

Here we describe the overall structure and design of the web site and how updates are carried out.

4.1. *Data Extraction and Sorting*

The HZG is currently not a stand-alone service but relies upon the data curation of the EDE. The HZG code is executed periodically to ensure that the catalog and data products remain in sync with the services of the EDE. When executed, the code uses a 'wget' command to extract all of the current data from the EDE and then identify the columns of the output file which are needed by the HZG. These columns are then sorted by the planet name and output to a new file ready to be processed by the site construction code.

The HZG retains a copy of the previous data file for the purposes of comparison. Specifically, the code checks for new planets or any changes that may have occurred in the parameters for known planets. If no changes are detected then the code halts at this point and any alterations that may have been made are restored.

4.2. *Automated Reconstruction*

The philosophy of the HZG design is accuracy and sustainability such that it can continue to provide useful results which keep pace with the current rate of exoplanet detection. The optimal path to reach this goal is to avoid data entry which dramatically increases maintenance and the introduction of errors. The site update is initiated via a single command which executes a shell script. As described in Section 4.1, the script first retrieves the most recent data and checks for changes. If there are new planets and/or parameters then the script proceeds to execute a series of FORTRAN programs which perform the necessary calculations and html modifications to incorporate the additional information.

The flowchart shown in Figure 2 summarized how the update and reconstruction of the web site functions. When changes to the database are necessary, the update page is modified with new planets added and/or changes to planetary parameters. The next step is to update the summary plot shown on the main page and the table page. It is computationally inexpensive to completely recreate these items rather than attempt to only modify those values which have changed. However, the next step of creating the figures in the gallery and the movies is time-consuming and so this step is only initiated where changes are required. The script finally recreated the index (main) page before stopping. The script also has

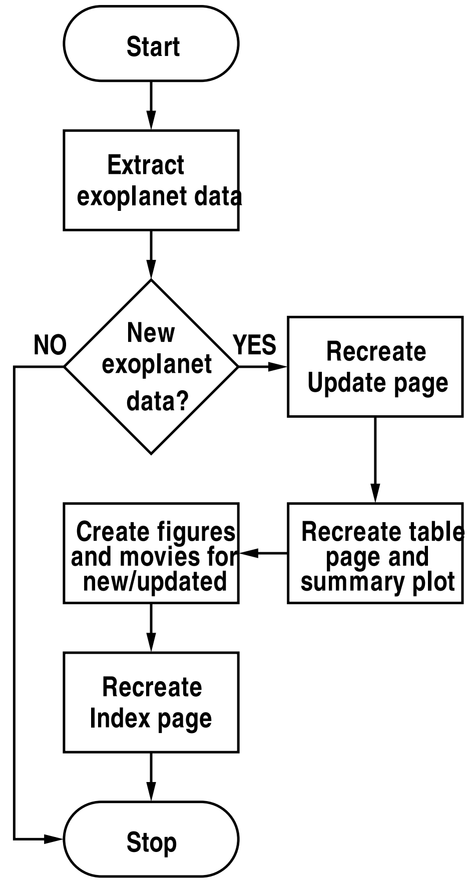

FIG. 2.— A flowchart which summarizes the automated reconstruction process wherever the HZG update code is executed.

an optional flag which, if used when executed, forces the complete reconstruction of the entire site including all the figures and movies.

The revised version of the site is built at a temporary location where the contents may be reviewed for accuracy and bug-related issues. Once statisfied that the update has been successfully completed, the new version is transferred to the operational location.

4.3. *The Table, Gallery, and Movies*

The three main services provided by the HZG are a table of derived planetary properties, a gallery of the planetary orbits with respect the their HZ, and movies which provide a visual aid for the varying predicted planetary temperatures.

The table includes the basic orbital properties of the planet, the percentage of the orbital phase spent within the HZ, and calculated temperatures at apastron and periastron for both the well-mixed and hot-dayside models (see Section 3.3). The table is sortable on any of these columns such that it can used to easily select targets of interest. For example, shown in Table 2 is a subset of the complete table in the HZG which includes those planets which spend 100% of their time within their stars HZ. We have only included the temperature columns in this truncated table. The HZG additionally allows the user to click on any of the planet names to load the location of that system with the Gallery section.

The Gallery section includes up to three plots per sys-

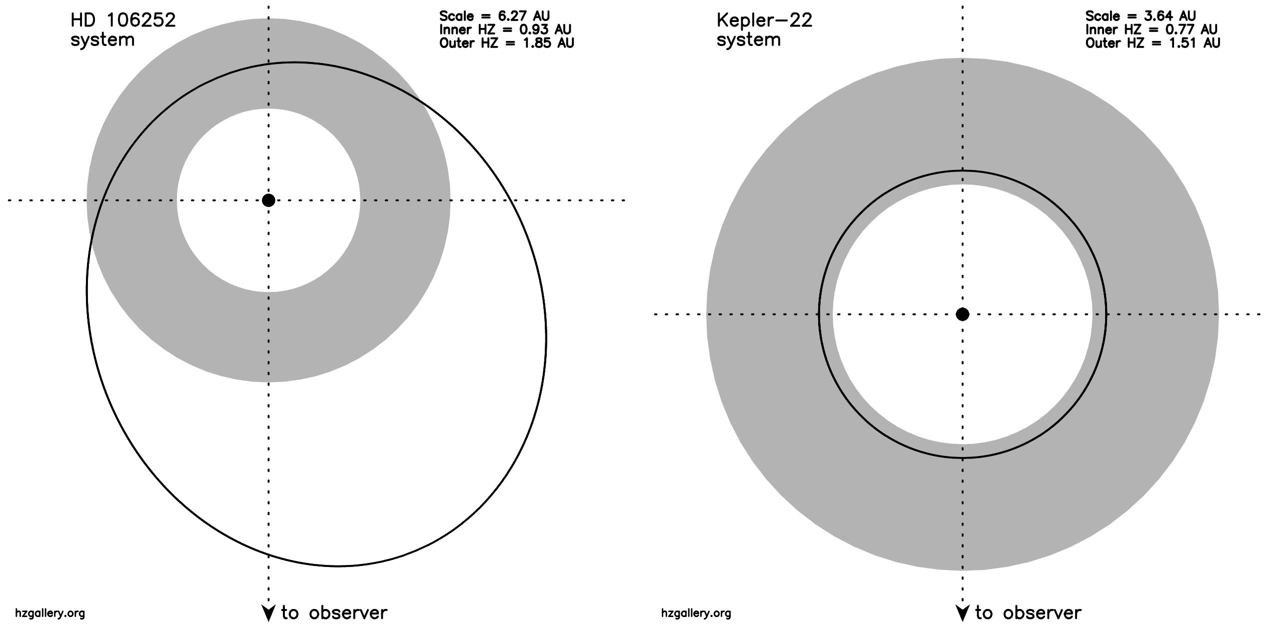

Fig. 3.— Two examples of orbits represented in the Gallery section of the HZG: HD 106252b (left) and Kepler-22b (right).

TABLE 2
Some planets which spend 100% of their time within the HZ.

Planet	$T^a_{\rm eff}$ (K)	$T^b_{\rm eff}$ (K)	$T^c_{\rm eff}$ (K)	$T^d_{\rm eff}$ (K)
tau Gru b	279	235	260	219
mu Ara b	322	271	283	238
Kepler-22 b	340	286	340	286
HD 99109 b	296	249	271	228
HD 45364 c	341	286	309	260
HD 38801 b	349	294	349	294
HD 28185 b	326	274	310	261
HD 23079 b	302	254	272	229
HD 221287 b	358	301	330	278
HD 188015 b	328	276	286	240
HD 16760 b	288	243	270	227
HD 108874 b	348	293	306	257
HD 10697 b	289	243	262	220
HD 10180 g	296	249	296	249
55 Cnc f	328	276	328	276

Note. — $T^a_{\rm eff}$: periastron, hot-dayside; $T^b_{\rm eff}$: periastron, well-mixed; $T^c_{\rm eff}$: apastron, hot-dayside; $T^d_{\rm eff}$: apastron, well-mixed.

tem depending in the location of inner and outer planets with respect to their HZ. The purpose of this is to accommodate the plotting of systems whose planetary orbits occupy a wide range of orbital radii. In Figure 3 are shown two examples from the HZG which demonstrate the diversity of these figures. HD 106252 b is in a 1531 day orbit whose periastron occurs within the HZ of its star. Only 17% of the total orbital phase occupies the HZ though since the planet is moving faster near periastron. This may be contrasted with the case of Kepler-22 b, also shown in Figure 3. The discovery of this planet was recently announced by Borucki et al. (2011c). Independent calculations by the HZG code confirm that the planet does indeed spend 100% of the orbit within the HZ.

Finally, the Movies section of the HZG provides users with animations for individual planetary orbits, available in MPEG-2 and MPEG-4 formats. The animations track the star-planet separation and calculated effective temperatures for the well-mixed atmospheric model. This is particularly useful for eccentric orbits where the temperature range can be substantial. The animations are divided into 200 frames of equal time increments per orbit which aids in the animation resolution for highly eccentric orbits during periastron passage.

5. CONCLUSIONS

The rate of exoplanet discoveries is continuing to increase, both with the radial velocity and transit methods. As the sensitivity and time baseline of the methods improve, the orbits of the discovered planets are increasingly being found to lie in the HZ of their host stars or beyond. This is a crucial step in identifying planets which are best suited for follow-up activities related to habitability and astrobiology.

The HZG seeks to provide a service in an easily maintainable way in order to keep up with the discovery rate. The HZG mostly includes planets whose host stars are relatively bright since they were primarily discovered using the radial velocity technique. The advantage of this is that these stars lend themselves to more accessible follow-up observations which can be better used to characterize those planets.

The structure of the site allows for automatic updates and reconstruction in a very short period of time. The figures and movies are intended for use in both scientific and public contexts and can be easily transported into any presentation. The tools allow the user to determine which known planets spend substantial time in their Habitable Zones and to visualize their orbits and also perform general investigations into the demographics of these targets. The HZG will continue to adapt to the needs of the exoplanet community and further develop tools as needed.

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