KEPLER INPUT CATALOG: PHOTOMETRIC CALIBRATION AND STELLAR CLASSIFICATION

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ABSTRACT

We describe the photometric calibration and stellar classification methods used by the Stellar Classification Project to produce the Kepler Input Catalog (KIC). The KIC is a catalog containing photometric and physical data for sources in the Kepler mission field of view; it is used by the mission to select optimal targets. Four of the visible-light (g,r,i,z) magnitudes used in the KIC are tied to Sloan Digital Sky Survey magnitudes; the fifth (D51) is an AB magnitude calibrated to be consistent with Castelli & Kurucz (CK) model atmosphere fluxes. We derived atmospheric extinction corrections from hourly observations of secondary standard fields within the Kepler field of view. For these filters and extinction estimates, repeatability of absolute photometry for stars brighter than magnitude 15 is typically 2%. We estimated stellar parameters \( \{T_{\text{eff}}, \log(g), \log(Z), E_{B-Y}\} \) using Bayesian posterior probability maximization to match observed colors to CK stellar atmosphere models. We applied Bayesian priors describing the distribution of solar-neighborhood stars in the color–magnitude diagram, in \( \log(Z) \), and in height above the galactic plane. Several comparisons with samples of stars classified by other means indicate that for 4500 K \( \leq T_{\text{eff}} \leq 6500 \) K, our classifications are reliable within about \( \pm 200 \) K and 0.4 dex in \( \log(g) \) for dwarfs, with somewhat larger \( \log(g) \) uncertainties for giants. It is difficult to assess the reliability of our \( \log(Z) \) estimates, but there is reason to suspect that it is poor, particularly at extreme \( T_{\text{eff}} \). Comparisons between the CK models and observed colors are generally satisfactory with some exceptions, notably for stars cooler than 4500 K. Of great importance for the Kepler mission, for \( T_{\text{eff}} \leq 5400 \) K, comparison with asteroseismic results shows that the distinction between main-sequence stars and giants is reliable with about 98% confidence. Larger errors in \( \log(g) \) occur for warmer stars, for which our filter set provides inadequate gravity diagnostics. The KIC is available through the MAST data archive.

Key words: catalogs – methods: data analysis – surveys – techniques: photometric

Online-only material: machine-readable and VO tables

1. INTRODUCTION

The Kepler mission (Borucki et al. 2010) surveys some \( 1.6 \times 10^5 \) stars in a field covering roughly 150 deg², watching for short-lived dips in brightness that may signal transiting planets. Of special interest to Kepler are transits by Earth-size planets, which, if they involve Sun-size stars, give relative depths of about \( 10^{-4} \), near to the practical limit of precision accessible by Kepler. For a planet of given size, the transit depth scales inversely as the cross-sectional area of the parent star. For this reason, the detectability of Earth-size planets depends strongly on the typical stellar radius of the sample of stars that Kepler observes. The number of stars that Kepler can follow is limited by telemetry bandwidth, and is considerably smaller than the total number of stars in Kepler’s field of view (FOV) that allow useful photometric precision. Thus, from an early stage the Kepler team recognized the importance of characterizing the radii of stars in the Kepler FOV, to prevent large-radius stars (e.g., giants) from taking slots on the target list away from smaller stars with better planet-detection prospects. The project instituted the Stellar Classification Project (SCP) in response to this need. The SCP’s goal was to provide, for all plausible target stars in the Kepler FOV, estimates of important stellar parameters. These were principally the radius \( R \), effective temperature \( T_{\text{eff}} \), and apparent magnitude \( K_P \) (i.e., as seen by the Kepler photometer) but also, to the extent possible, the surface gravity parameter \( \log(g) \) and the metallicity parameter \( [Z] \equiv \log(Z/Z_\odot) \).

Because of the sky area and large number of stars involved, we deemed spectroscopic classification to be impractical, and instead chose to use broadband photometry, augmented by intermediate-band photometry using our custom D51 filter, which is sensitive to surface gravity and to metallicity. The results of this photometric reconnaissance of the Kepler FOV were federated with other suitable catalogs, such as the Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006), USNO-B1.0 (Monet et al. 2003), Hipparcos (ESA 1997; Perryman et al. 1997), Tycho-2 (Hog et al. 2000), and UCAC2 (Zacharias et al. 2004) to become the Kepler Input Catalog, or KIC. The aim of this paper is to describe how we carried out the photometric analysis and stellar classification for the KIC. Details of the observing routine and of the photometric reductions will be given elsewhere, but a brief summary follows.

We took all observations with the 1.2 m reflector at the Fred Lawrence Whipple Observatory on Mt. Hopkins, AZ. During the course of the project, we used a succession of three CCD cameras: the 4-Shooter (from the project’s first data in 2003 September = JD 2,452,895 until 2004 August = JD 2,453,233), the MiniCam until 2005 September = JD 2,453,626, and the KeplerCam thereafter. All of these cameras had thinned, back-illuminated 4 K \( \times 4 \) K pixel formats covering fields roughly 22 arcmin², but the details of their detectors, noise properties, sensitivity, and geometry varied from camera to camera. To cover the entire Kepler field with these cameras required 1600 pointings with minimal (roughly 10%) overlap between adjacent pointings. We began
observations with seven filters (nominal Sloan $u$, $g$, $r$, $i$, $z$, and two special-order intermediate-bandwidth filters we named $D51$ and $G_{\text{red}}$). Both of the latter had bandpasses of about 15 nm. The $D51$ filter, which was modeled after the Dunlap Observatory $D551$ filter, was centered at 510 nm, and the $G_{\text{red}}$ filter at 432 nm. In practice, we soon learned that the $u$ and $G_{\text{red}}$ filters required excessive exposure times, so we took very few observations with these filters, and we will henceforth ignore them for the most part.

For the great majority of the observations, we cycled through all of the filters at one pointing before moving to the next pointing. Each filter sequence consisted of both long and short integrations in the filters $g$, $r$, $i$, $z$. For $g$ and $z$, the long and short exposure times were 30 s and 3 s; for $r$ and $i$ they were 20 s and 2 s. Filter $D51$ got only a single long integration of 160 s. We identified two pointings containing stars that we used as secondary photometric standards; we returned to one of these fields about once per hour so as to have a fairly dense time sampling of the atmospheric extinction. We selected these two fields so that they included the open clusters NGC 5179 and 5161; the centers of these fields lie at (R.A., decl.) of $\{294.56, +46.58\}$ and $\{295.28, +40.23\}$ (decimal degrees), and they contained 455 and 1181 secondary standard stars, respectively. Our intention, which we almost realized, was to visit each pointing at least three times under conditions of good transparency, never returning twice to a given pointing (except the standards) on the same night.

We used a special-purpose pipeline to reduce the image data to catalogs of star positions and apparent magnitudes (uncorrected for atmospheric extinction). This pipeline made the usual corrections for bias and flat field, identified star-like objects, used DAOPHOT (Stetson 1987) to perform point-spread function (PSF) fitting photometry and computed aperture corrections based on isolated bright stars, and fit an astrometric model to the stellar positions. We fitted the stellar PSFs using the DAOPHOT “Penny1” function, which has a Gaussian core and Lorentzian wings. The pipeline returned a list of detected stars (and star-like objects such as radiation events), with positions, magnitudes, sky background estimates, and shape parameters for each. Also returned were error estimates and various parameters relating to the image as a whole, including the starting time, exposure time, and estimated seeing width. All of these data were saved in an ASCII file and passed to the software that is the subject of the current paper. Here we describe the methods used for photometric calibration, correction for atmospheric extinction, and for interpretation of the resulting absolute photometry in terms of the physical parameters of the prospective Kepler target stars.

2. STRATEGY

The processes and software described here represent an intermediate stage in the processing of SCP data for the KIC. The functions of the procedure described here were fourfold. First, it ingested the raw photometric catalogs provided by the photometry pipeline into a group of databases that allowed convenient processing. Second, it estimated the atmospheric extinction suffered by each measurement, and corrected the instrumental stellar magnitudes to yield calibrated ones. Third, it combined the calibrated magnitudes with other information (e.g., stellar atmosphere models) to estimate the physical parameters of each observed star, including $T_{\text{eff}}$, log($g$), [Z], radius $R$, mass $M$, and interstellar reddening $E_{B-V}$. Last, it discarded those stars (and putative stars) for which estimates were deemed unreliable.

Data ingestion was a straightforward process, with its details determined almost entirely by the database structure that was defined at the outset. Correction for atmospheric extinction was also simple in concept, depending mostly on the model adopted for extinction, and on the criteria for estimating the parameters in that model. Many of the latter decisions were guided by the choices made for the Sloan Digital Sky Survey (SDSS; Fukugita et al. 1996; Smith et al. 2002), since our filter set was similar to theirs.

 Stellar parameter estimation was the most difficult part of the project. The underlying problem is that, for the purposes of the Kepler project, the most interesting parameter is the stellar radius $R$, which is to say log($g$), but the (mostly) broadband filters we used provide measurements that are almost entirely insensitive to this parameter. The intermediate-band $D51$ filter provides some gravity sensitivity, while for M-type stars, the $J-K$ color (obtained from the 2MASS catalog; Skrutskie et al. 2006) provides a gravity measure. Nevertheless, the photometric information that we could obtain on the timescale necessary for the project was barely sufficient for our needs. It therefore made sense to perform the parameter estimation in the context of astrophysical information external to our photometry. We did this by adopting various distributions known for stars in the Sun’s neighborhood as Bayesian priors, and taking as each star’s physical parameters the ones that maximized the posterior probability of obtaining the observed magnitudes and colors. As amplified below, this method had several drawbacks, but it did use the available data to far greater advantage than do methods that ignore the prior constraints. Many of the methods described below are devoted to ways of quantifying the needed prior distributions.

Finally, filtering out bad data and formatting the result for the next stage in KIC assembly was also straightforward, consisting mostly of identifying spurious detections, failed fits, and so on. The criteria for passing results to the final KIC are described below.

3. CALIBRATED PHOTOMETRY

The data received from the photometric pipeline consisted of one ASCII file for each image taken at the telescope. Each file contained a header and two data tables. The header contained information relating to the image as a whole: Julian date, telescope coordinates, filter, exposure time, as well as various quantities such as PSF width, derived in the course of the analysis. The first data table contained the stars’ coordinates obtained from an astrometric fit, their instrumental magnitudes, the local sky brightness, and various error estimates and goodness-of-fit parameters. The second table contained the coordinates, $J$, $H$, and $K$ magnitudes, and unique integer identifier for all of the stars in the 2MASS catalog (Skrutskie et al. 2006) that fell within the field covered by the image in question.

To allow simple comparisons with results from the SDSS, we wished to place our photometry as nearly as possible on the Sloan system. Unfortunately the Kepler field lies entirely at low galactic latitude, so at the time we started the project, there were no SDSS data available inside the Kepler field. (This is no longer true, though SDSS coverage of the Kepler field remains very incomplete, with only a few square degrees of overlap in DR7.) We therefore chose a set of eight fields elsewhere in the sky, each with data available from SDSS DR1 (Abazajian et al. 2003; Stoughton & Jester 2004), to serve as our photometric standards. Subsequent SDSS data releases, notably DR2, had improved photometry. These improvements applied mostly to galaxies,
however. Changes in methods for fitting “model” magnitudes gave modest reductions in the scatter for stellar magnitudes, but left the mean zero points unchanged (Abazajian et al. 2004).

We chose the standard fields first to span a range of R.A. surrounding the Kepler field, and also so that each contained a fairly wide range of stellar colors (but even so, there were many fewer blue than red stars in the standard fields). There were 284 primary standard stars; ignoring 6 evident outliers (which varied fewer blue than red stars in the standard fields). There were 284 of the primary standard stars, along with their photometric indices and the stellar parameters that we inferred for these stars.

### Table 1

| R.A. | Decl. | u  | g  | r  | i  | z  | D51 | J   | H   | K   | Kp | T_eff | log(g) | log(Z) | log(R_e) |
|------|-------|----|----|----|----|----|-----|-----|-----|-----|----|-------|--------|--------|----------|
| 112.83372 | 29.07580 | 17.829 | 16.077 | 15.434 | 15.226 | 15.141 | 15.838 | 14.221 | 13.842 | 13.773 | 15.481 | 5386.4 | 4.483 | -2.540 | -0.021 |
| 112.83971 | 29.02154 | 16.745 | 15.344 | 16.282 | 14.527 | 14.407 | 15.519 | 13.493 | 13.037 | 12.996 | 16.047 | 6057.3 | 4.503 | -0.187 | 0.093 |
| 112.84009 | 29.07181 | 16.619 | 15.187 | 14.871 | 14.405 | 14.308 | 15.054 | 13.361 | 13.044 | 12.941 | 14.640 | 6023.0 | 4.334 | -1.577 | 0.076 |
| 112.85278 | 29.14279 | 17.426 | 16.191 | 15.712 | 15.549 | 15.502 | 15.995 | 14.657 | 14.362 | 14.285 | 15.742 | 6026.0 | 4.441 | -1.955 | 0.019 |
| 112.86972 | 28.85981 | 17.497 | 16.380 | 16.038 | 15.898 | 15.861 | 15.039 | 14.877 | 14.701 | 16.043 | 6257.0 | 4.404 | -1.608 | 0.043 |
| 112.87161 | 29.14310 | 18.962 | 17.127 | 16.438 | 16.205 | 16.144 | 16.876 | 15.185 | 14.740 | 14.739 | 16.482 | 5234.0 | 4.539 | -2.502 | -0.057 |
| 112.87298 | 28.92986 | 18.938 | 16.629 | 15.625 | 15.245 | 15.023 | 16.296 | 13.951 | 13.371 | 13.272 | 15.660 | 4614.0 | 4.583 | -1.682 | -0.129 |
| 112.87424 | 29.00252 | 17.530 | 16.366 | 15.968 | 15.828 | 15.772 | 16.191 | 15.005 | 14.787 | 14.676 | 15.990 | 6201.0 | 4.427 | -1.835 | 0.030 |
| 112.88787 | 29.02796 | 17.541 | 15.929 | 15.306 | 15.030 | 14.932 | 15.696 | 13.989 | 13.586 | 13.525 | 15.300 | 5559.0 | 4.426 | -2.504 | 0.017 |
| 112.88976 | 28.88614 | 17.904 | 16.576 | 16.065 | 15.903 | 15.816 | 16.372 | 14.951 | 14.608 | 14.494 | 16.105 | 5988.0 | 4.451 | -1.995 | 0.013 |

(This table is available in its entirety in machine-readable and Virtual Observatory (VO) forms in the online journal. A portion is shown here for guidance regarding its form and content.)

After obtaining a few dozen nights of data with all of the secondary standard stars, some stars could be identified as unusable because they showed large temporal variability, or they were members of close binaries, or for similar reasons. We removed these from the list of secondary standard stars.

### 3.1. Estimating Atmospheric Extinction Parameters

The extinction model was based on that used for the SDSS standard star grid (Smith et al. 2002), although in practice we found several of the coefficients in this model to be difficult or impossible to measure on a nightly basis, and we therefore set them to constant (sometimes zero) values. We partitioned our photometric observations into time-contiguous units called blocks, with a block being a unit of data that could be adequately described by a single set of extinction coefficients. Almost always, blocks corresponded to entire observing nights. Sometimes, however, changing weather conditions made it desirable to subdivide a night into multiple blocks.

For filter $i$ and an instance $j$ (within a block) of observing a particular star $k$, our extinction model represented the observed magnitude $m_{ikj}$ as follows:

$$m_{ikj} = m_{0ik} + a_i + k_i(X_{kj} - X_0) + b_i(C_{ik} - C_{0}) + c_i(C_{ik} - C_{0})(X_{kj} - X_0). \quad (1)$$

Here, $m_{0ik}$ is the true magnitude of star $k$ in filter $i$, $X_{kj} - X_0$ is the difference between the airmass of star $k$ at instance $j$ and a standard airmass $X_0$. $C_{ik}$ is the color of star $k$ defined using a particular pair of filters similar in wavelength to the filter $i$, and $C_{0i}$ is the color of a “typical” star using that same filter pair. The coefficients $a_i$, $k_i$, $b_i$, and $c_i$ are parameters that may be chosen to give the best fit to the observations.

Note that by writing the extinction as above, the “standard” magnitude of a star corresponds to what one measures when the star lies at airmass $X_0$, not when it is outside the atmosphere. One advantage of this approach was to reduce the effect of errors in estimation of the extinction per unit airmass (the $k_i$). Also, this choice of airmass coordinate tends to reduce correlated errors between $a_i$ and $k_i$. For this analysis, we took the standard airmass $X_0$ to be 1.215. We chose this value to coincide with the value 1.3 adopted by SDSS, with allowance for the higher altitude (hence lower air density) of the Sloan telescope relative to the 1.2 m telescope at Mt. Hopkins.

Note further that the extinction model makes no explicit assumption about, or measurement of, the site’s mean extinction as a function of wavelength. All information about this behavior...
is contained in the coefficients $a_i$ and $k_i$. As will be shown below, these vary enough from night to night that they call into question the utility of the site’s mean color dependence of extinction.

In practice, we found that the observations of standard stars on a single night ordinarily did not suffice to give a reliable estimate of all of the coefficients in the extinction relation. Indeed, we obtained best results by fitting for the coefficients $a_i$ each night, using values averaged over an entire observing season for the coefficients $k_i$, and taking the coefficients $b_i$ from theoretical calculations based on model stellar fluxes and the estimated wavelength responses of the various filters. We took the coefficients $c_i$ to be uniformly zero. Figure 1 shows the time variation of the coefficients $a_i$ for all but 2 of the 205 nights for which we have data. The zero points in this figure have been arbitrarily shifted for plotting clarity. The zero points are arbitrary, but time variations of the $a_i$ coefficients have physical interest. Significant jumps in the $a_i$ coefficients occurred with the inauguration of new cameras (changing from 4-Shooter to MiniCam about JD 2,453,233, and from MiniCam to KeplerCam about JD 2,453,626). There also are trends and seasonal variations visible in these data, notably a loss of about 20% sensitivity in the telescope/KeplerCam system since the time the KeplerCam was installed.

After estimating the $a_i$ coefficients, we produced a second estimate of the extinction and the quality of the night’s data. For this purpose we used only selected stars observed at each reference pointing to estimate the $a_i$ and $k_i$ coefficients for each night. We chose stars so that exactly the same subset of stars in each reference pointing were always used in the fitting process for a single night. This minimized errors arising from errors in the assumed magnitudes of the reference stars. We thus obtained nightly estimates of the $k_i$ coefficients as well as the $a_i$ (although the $k_i$ are well determined on a little less than half of the nights). Figure 2 illustrates such a fit for one fairly typical night. Frequent returns to reference fields within the Kepler FOV allow accurate fits for $k$ on photometric nights, and reveal the times and severity of time-varying extinction on the (more common) non-photometric nights. The bottom panel shows residuals around the fits plotted against the measured image FWHM, measured in arcseconds. An important part of the photometric reduction process was to perform seeing–dependent corrections for the fraction of starlight falling outside the boundaries of the effective photometric aperture. On most nights, this plot showed no clear trend of residuals versus FWHM, but on some (such as the one illustrated here), there is slight evidence for such a trend. This indicates occasional errors in the aperture-correction procedures, which must compromise the photometry at some level. This problem was sporadic and relatively minor, making it difficult to diagnose. Indeed, we never succeeded in tracking this problem to its root, though plots such as those in Figure 2 allowed us to identify problematic nights. Also evident from this plot is the relatively large FWHM of the images on the night displayed here. Indeed, the images were broad on a large fraction of our observing nights; the image FWHM was below 1.7 arcsec only about 2% of the time, and the median FWHM for all of our images was 2.5 arcsec. Because of this relatively poor spatial resolution, the KIC is ineffective at distinguishing the components of binary stars, if their component separation is even moderately small.

Figure 3 shows the variation of the $k_i$ with time, measured on the nights when we judged the observations to be consistent enough to allow a measurement. The night-to-night variations tend to be large (up to 40% of the mean values), but they are also well correlated among filters. Thus, there is good evidence for variations dominated by large-particle aerosol extinction, having little wavelength dependence, and varying on a timescale of one to a few days. The SCP photometry could be improved by putting this information about the $k_i$ back into the extinction model on a nightly basis. We have not yet done this, however. The corrections would not be large, in any case. Given the size of the errors in $k$ and the typical difference between the airmasses of actual observations and the standard airmass ($X_0 = 1.215$), corrections in the observed magnitudes would be at most

![Figure 1](https://example.com/figure1.png)

**Figure 1.** Combined atmospheric and instrumental coefficients $a_i$ (see Equation (1)) for the $g$, $D51$, $r$, $i$, and $z$ filters for 203 of the 205 nights on which KIC data were obtained. The remaining two nights gave values that are extreme outliers, falling outside the range of these plots. Zero points on these curves have been shifted for plotting convenience. Note the color dependence of the temporal variations, which tend to be larger in blue filters than in red. Vertical dashed lines indicate the dates of transition between CCD cameras.
Figure 2. Plot of g extinction data on a representative (mildly non-photometric) night. The top panel shows extinction as a function of airmass. Points plotted as diamonds were obtained before the meridian transit of the standard field; those plotted as triangles were obtained after it. Vertical bars indicate the interquartile spacing of results from the 20 stars used to estimate the extinction. The diagonal dashed line is the result of a robust linear fit to the extinction values, with coefficients tabulated in the upper left corner of the plot. The bottom panel shows residuals around this fit plotted against the time-varying FWHM of the stellar point-spread function.

Figure 3. Variation in the $k_i$ coefficient (extinction per unit airmass in the $i$th filter), shown as a function of date, for nights for which reliable linear fits to the extinction could be obtained, during a part of one observing season. The time span shown here was one of the most variable that we encountered in five seasons of observing, but is nonetheless typical in its variability within a factor of 1.5. Filters g, D51, r, i, z are shown in order from top to bottom of the plot. Night-to-night variations tend to be not only correlated, but of similar size among the filters. An exception is the z filter, in which the extinction is evidently affected by a different process than at shorter wavelengths. We believe that this process is extinction from water vapor.

0.09 mag, and would be less than 0.03 mag for about 90% of the observations.

After estimating the extinction coefficients for a block of data, we estimated the $m_{V0}$ magnitudes averaged over visits for every star that was observed in any filter within that block. This process identified every star that was observed at any time during a given block, and then gathered together every observation to be found in the databases for each of those stars.

Of the 1600 pointings that span the entire Kepler field, none have zero visits with acceptable photometry, 8% were visited only once, 71% twice, 17% three times, and 3% four or more times. Two pointings, corresponding to secondary standard fields, were visited more than 260 times each. For pointings with at least four visits, we computed a pseudo-rms from the interquartile dispersion $q$ as $\text{rms} = q/1.349$; this formula gives the expected result for a Gaussian distribution, but is insensitive to a small proportion of extreme outliers. We identified outliers as measurements differing from the median by more than five times this pseudo-rms, and discarded them from the fit to give robust minimum-$\chi^2$ magnitude estimates.

3.2. Precision of Corrected Magnitudes

We assessed the precision (in the sense of repeatability) of stellar magnitude estimates by collecting all the measurements
for each star in the secondary standard fields (each having typically hundreds of individual observations), and computing the scatter in these time series. We did this for a set of 5652 stars brighter than \( r = 19.5 \), each having at least 50 individual observations (and most having more than 200). For each star we estimated the time-series pseudo-rms as described above. We then computed for each filter the median pseudo-rms taken over stars, in 1 mag bins centered on integral values of the (time-series) median magnitude. The resulting pseudo-rms scatter as a function of stellar magnitude in each filter is plotted in Figure 4. The photometric errors are dominated by brightness-independent processes (probably errors in the atmospheric extinction correction) in all filters for stars brighter than about magnitude 14; for fainter magnitudes, photon statistics begin to have an effect, and become dominant by about magnitude 16. For the stars brighter than magnitude 14, the repeatability of extinction-corrected measurements is about 2%, almost independent of filter.

The rms precision of color estimates (i.e., differences between magnitudes measured in different filters) was usually somewhat better than for magnitudes (typically 1.5%), because much of the scatter in the extinction-corrected magnitudes comes from extinction processes that have long timescales, whereas the two measurements making up a color estimate were almost always taken within a few minutes of each other.

4. KEPLER MAGNITUDES

To estimate planet detectability for each potential target star, the Kepler mission required information about stellar magnitudes as they would be measured by the Kepler photometer. These are known as the Kepler magnitudes, or \( K_p \). For this purpose we estimated Kepler magnitudes using photometry in standard bandpasses. The \( K_p \) values that we computed for each star are tabulated in the KIC along with the other photometry. The ideal Kepler wavelength response function \( K_I(\lambda) \) may be found in Koch et al. (2010) and on the Kepler Web site.\(^4\) The bandpass may be roughly described as having sharp edges,

with the center being slightly peaked; it has more than 10% response in the wavelength range \( 420 \text{ nm} \leq \lambda \leq 890 \text{ nm} \). Thus, the bandwidth is about 470 nm and the effective wavelength, for a spectral energy distribution corresponding to a 5500 K blackbody, is approximately 665 nm.

The \( K_p \) are defined as AB magnitudes (Oke 1974; Smith et al. 2002), derived from each target’s calibrated \( g, r, i \) magnitudes. To compute them, we started with the published (Castelli & Kurucz 2004) grid of stellar atmosphere model fluxes, and used these and the known, tabulated wavelength response functions to compute the rate of photoelectron detections from each of the model flux distributions for a wide range of stellar types (these were functions of \( T_{\text{eff}}, \log(g), \) and metallicity) using each of the filters \( \{g, r, i\} \) and using the “ideal” Kepler bandpass \( K_I \) described above. We then attempted to approximate these synthetic magnitudes as they would be measured in the band \( K_I \) in terms of linear combinations of the \( \{g, r, i\} \) magnitudes for the corresponding models. Based on a visual inspection of the relationships, we defined these combinations on each of several contiguous ranges of some fiducial color, e.g., \( (g - r) \); for operational purposes, \( K_p \) is defined only in terms of these combinations of magnitudes in standard filters.

Complications arise because not all KIC stars have valid values for all of the filters \( \{g, r, i\} \), and moreover many stars (which appear in the KIC by virtue of federation with non-SCP catalogs) have none of them. The Kepler magnitude \( K_p \) is thus defined by a complex set of rules, depending on what information is available about the star in question. Policy demanded that the KIC contain a Kepler magnitude for every star known to lie within the field. Thus, the rules covered cases in which information was scant and accurate transformations were not possible.

We note that the definition of \( K_p \) as a linear combination of observed magnitudes in standard bands means that the effective wavelength response function that one should ascribe to \( K_p \) is ill-defined. Apart from the ambiguity arising from which bands may have been used in computing \( K_p \), it develops that (because of the nonlinear relation between flux and magnitude) the effective bandpass for \( K_p \) is also a function of the stellar color.

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\(^4\) http://keplergo.arc.nasa.gov/CalibrationResponse.shtml
Thus, the magnitudes $K_p$ are entirely defined by the following Equations (2)–(6). A further result of the method for computing $K_p$ is that the photometric zero point for $K_p$ is not exactly on the AB system but is rather a weak function of stellar color. Because we chose the weighting coefficients for the various bandpasses based on a color-dependent fit to integrals over $K_T(\lambda)$, the part of the zero-point dependence that is linear in color has been absorbed by the weighting coefficients. Higher-order terms remain, however. At worst, for stellar colors at the extreme ends of the range that one encounters, these higher-order terms amount to about 0.05 mag.

For stars with SCP photometry, the computation rules are as follows. If only one of $\{g, r, i\}$ is valid, then $K_p$ is equal to the valid magnitude.

If only $g$ and $r$ are valid, then

$$K_p = 0.1g + 0.9r, \quad (g - r) \leq 0.8, \quad (2a)$$

$$K_p = 0.2g + 0.8r, \quad (g - r) > 0.8. \quad (2b)$$

If only $g$ and $i$ are valid, then

$$K_p = 0.55g + 0.45i, \quad (g - i) \leq -0.05. \quad (3a)$$

$$K_p = 0.3g + 0.7i, \quad (g - i) > -0.05. \quad (3b)$$

If only $r$ and $i$ are valid, then

$$K_p = 0.65r + 0.35i, \quad (r - i) \leq 0.673, \quad (4a)$$

$$K_p = 1.2r - 0.2i, \quad (r - i) > 0.673. \quad (4b)$$

If $\{g, r, i\}$ are all valid, then

$$K_p = 0.25g + 0.75r, \quad (g - r) \leq 0.3, \quad (5a)$$

$$K_p = 0.3g + 0.7i, \quad (g - r) > 0.3. \quad (5b)$$

The linear combinations in Equations (3), (4), and (5) yield $K_p$ magnitudes that reproduce the “ideal” magnitudes $K_T$ with typical errors of about 0.03 mag for stars with $T_{eff} \geq 3500$ K, though for extreme stellar parameter values, the errors may reach ± 0.2 mag. In the case in which only $g$ and $r$ are known (Equation (2)), the disagreement between $K_p$ and $K_T$ may reach 0.6 mag for very cool M-type stars, in the sense that the computed $K_p$ is fainter than $K_T$.

For stars imported from the Tycho-2 parent catalog, which gives $B_T$ and $V_T$ magnitudes, we estimate equivalent Sloan magnitudes $g_T$ and $r_T$ as

$$g_T = 0.54B_T + 0.46V_T - 0.07, \quad (6a)$$

$$r_T = -0.44B_T + 1.44V_T + 0.12, \quad (6b)$$

and then compute $K_p$ using Equations (2a) and (2b).

For stars coming from any other parent catalog having both a blue and a red magnitude, we simply substituted these magnitudes for $g$ and $r$, respectively, and again used Equations (2a) and (2b).

Finally, for stars coming from parent catalogs that contain information in only one optical bandpass, $K_p$ is taken to be the reported magnitude in that bandpass. In this case, of course, very large errors (1 mag or more) may occur.

5. MODEL STELLAR ATMOSPHERES

The stellar classification process requires choosing among model stellar atmospheres (which have parameters $\{T_{eff}, \log(g), \log(Z)\}$) so as to best fit the photometric observations. We used model atmospheres by CK; these cover $3500 \, \text{K} \leq T_{eff} \leq 50,000 \, \text{K}$, $0 \leq \log(g) \leq 5.5$, and $-3.5 \leq \log(Z) \leq 0.5$, although not all gravities are represented at all temperatures.

The models provide fluxes as a function of wavelength. To convert these to stellar AB magnitudes (relative to an arbitrary zero point) we transformed the tabulated values from units of energy flux per unit wavelength to units of photon flux per unit frequency, multiplied the stellar flux by an estimate of the CCD response and by the estimated filter transmission functions, and integrated the result over frequency to give the rate of photoelectron production as a function of filter and of each of the parameters that characterize the model atmospheres. We took magnitudes in each of the filters to be on the AB magnitude scale. In operational terms, this was already the case for the filters $\{g, r, i, z\}$ and for the 2MASS magnitudes $\{J, H, K\}$; we therefore left the zero points in all of these filters untouched. For the D51 filter, we adjusted the zero point to force agreement with the CK model $g - D51$ colors as described in Section 3.

After computing the stellar magnitudes described above, we next formed differences to yield seven independent colors, viz., $(g - r), (r - i), (i - z), (z - J), (J - H), (H - K),$ and $(g - D51)$. The arbitrary zero point cancels from these differences, so these numbers are a representation of the spectral energy distribution of the stellar models that does not depend upon stellar radii or distances. Most of the operations that later tried to match stellar properties to observations relied on these seven colors.

To achieve near equality between observed colors and fluxes from the CK models, we transformed the latter in several ways. First, we adjusted the magnitude zero points for all filters except $i$ (which we adopted as standard, linked by definition to a small set of SDSS stars). We based these adjustments on comparisons with three sets of stars for which the photometric (and in some cases the physical) properties could be known with some accuracy from pre-existing data. These included a set of 4 Sun-like stars chosen from the list of SDSS standard stars (Smith et al. 2002), a set of 63–77 stars (depending on the filter involved) in the cluster M67, each of them known to be single from spectroscopic observations by W. Latham and S. Meibom, and having good photometry and spectroscopic classification (Montgomery et al. 1993; Sandquist 2004), and finally a set of some 500 probable cluster stars in a 2 deg square surrounding M67. For the last group, we first identified an optimally fitting stellar atmosphere model for each star that fell close to the M67 cluster isochrone, and then adjusted the magnitude zero points to minimize the mean difference between observed and predicted colors.

Second, we noted a serious disagreement between observed and model $(g - r)$ colors for stars cooler than 4000 K. Model $(g - r)$ colors based on the CK fluxes never exceed about 1.2, while many faint members of M67 and nearby field stars (which are almost certainly dwarfs of near-solar metallicity) have $(g - r)$ colors that approach 1.5. To allow more accurate modeling of the photometry for these stars, we applied ad hoc adjustments to the $(g - r)$ colors of all CK models with temperatures of 4000 K or less. These adjustments added to each model $(g - r)$ value an offset that depended only upon $T_{eff}$. The corrections applied were +0.179 at 4000 K, +0.289 at 3750 K, and +0.402 at 3500 K.
This ad hoc process improved the quality of fits considerably, but rendered the $T_{\text{eff}}$ scale in this range unphysical, at least so far as the $(g-r)$ color is concerned.

Third, we added smaller $T_{\text{eff}}$-dependent corrections to the colors $(r-i), (i-z), (J-H), (H-K)$]. These corrections were linear in temperature and equal to zero at $T_{\text{eff}} = 5000$ K, with slopes per 1000 K equal to $\{0.006, -0.021, -0.036, 0.011\}$, respectively. All of these adjustments were independent of $\log(g)$ and $\log(Z)$.

Last, we adjusted the $(g-D51)$ color in a way that depended both on $T_{\text{eff}}$ and on $\log(g)$: for $T_{\text{eff}} \leq 4300$ K, the revised model color $(g-D51)'$ was given by

$$(g-D51)' = (g-D51) - 0.23f_g(T_{\text{eff}}-4300)/1000,$$  

where the function $f_g(\log(g))$ was unity for $\log(g) \geq 3.5$, and for smaller $\log(g)$ decreased linearly with $\log(g)$ to zero at $\log(g) = 0$.

6. REDDENING

Interstellar reddening is significant for most of the stars in the Kepler field, so it was necessary to include it in the models of stellar colors. We assumed that the wavelength dependence of reddening is described by the formalism of Cardelli et al. (1989). In all cases we used $R_V = 3.1$, which Cardelli et al. found to be the typical value for diffuse interstellar dust clouds.

Strictly, the reddening suffered by starlight depends on parameters $\{T_{\text{eff}}, \log(g), \log(Z)\}$. The importance of this effect is fairly small, however, so for speed of computation, we precomputed redenennings for our filters and a range of stellar parameters. We then adopted the reddening vectors for typical stars in the Kepler field ($T_{\text{eff}} = 5000$ K, $\log(g) = 4.0, \log(Z) = 0$) as applying to all stars.

We estimated the strength of the reddening using a simple model of the dust distribution in the Milky Way. This model assumed that dust is distributed in a smooth disk aligned with the plane of the Milky Way, having an exponential decay of density with height above the plane. For all computations described here (except for certain test cases, such as parameter estimations for M67), we took the $e$-folding height for disk density to be 150 pc, which is slightly larger than suggested by recent estimates (Koppen & Vergely 1998 and Marshall et al. 2006 give 140 pc and 125 pc, respectively). We took the density in the plane to be such as to cause 1 mag of extinction in the V band in a path length of 1000 pc (Koppen & Vergely 1998).

7. FITTING STARS TO OBSERVATIONS: LINKED PARAMETERS

A star and the light we see from it may be characterized by many parameters, not all of them independent. These include not only its photometric colors, but also its apparent magnitude, distance, reddening, and intrinsic properties $\{T_{\text{eff}}, \log(g), \log(Z)\}$, mass $M$, radius $R$, and luminosity $L$. Different photometric measurements constrain different combinations of these parameters; to obtain sensible estimates of the intrinsic parameters, it is important to respect the relations that connect them.

We took our distinct observables to be the photometric colors (in the typical case for which $u$ and $G_{\text{red}}$ are unavailable, there are seven of these), the apparent magnitude in any one filter (we used $r$), and the galactic latitude $b$. The 11 parameters we wished to estimate were $T_{\text{eff}}, \log(g), \log(Z), M, R, L, BC_r, d, A_r, A_V, E_{B-V}$, where $BC_r$ is the bolometric correction for the $r$ band (in practice computed as $BC_r = BC_V + (V-r)$), $d$ is the distance in pc, $A_r$ and $A_V$ are the interstellar extinction in the $r$ and $V$ bands, and $E_{B-V}$ is the $B-V$ color excess due to interstellar extinction. But connecting these parameters are the relations

$$A_r = \kappa_r \int_0^d \exp(-s \sin b) ds$$  

$$A_V = A_r/0.88$$  

$$E_{B-V} = A_V/3.1$$  

$$L = R^2(T_{\text{eff}}/T_0)^4$$  

$$r = r_\odot - 2.5 \log L + BC_r + A_r + 5 \log d - 5$$  

$$\log(g) = \log(g)_\odot + \log M - 2 \log R,$$

where $\kappa_r$ is the assumed $r$-band interstellar extinction coefficient in magnitudes per pc, $R$, $M$, and $L$ are in solar units, $d$ and the dummy integration variable $s$ are in pc, $r_\odot$ is the Sun’s absolute magnitude in the $r$ band, and $A_r, A_V, BC_r, E_{B-V}$ are in magnitudes. The simple numerical relations between $A_r, A_V, \log(g)$, and $E_{B-V}$ result from integrating the Cardelli et al. model of interstellar reddening against typical (5000 K dwarf) stellar flux distributions, as described above.

Applying the above constraints reduced the number of unknowns from 11 to 5, but this was still an uncomfortably high-dimensional space to search for the best goodness of fit. Worse, given realistic errors in the data, we found that an unrestricted search in this space tended to lead to unphysical solutions in which various parameters were driven to extreme values in an attempt to balance misfits relative to the observations. To reduce these problems we adopted two further ad hoc relations, namely

$$BC_r = BC_r(T_{\text{eff}}, \log(g))$$  

and

$$M = M(T_{\text{eff}}, \log(g)).$$

The $BC_r$ relation is valid for fixed composition, and for computational purposes we simply adopted the results of the CK models for $\log(Z) = 0$. We justify the inaccuracies resulting from ignoring the $\log(Z)$ dependence by the relative scarcity of low-metallicity stars in the solar neighborhood.

The $M(T_{\text{eff}}, \log(g))$ relationship is true only in a statistical sense, because age and (to a lesser extent) metallicity effects cause the evolutionary tracks of stars of different mass to cross in the color–magnitude diagram (CMD). This causes inevitable ambiguity, especially for giants and subgiants. However, for the cool main-sequence stars that are of most interest to Kepler, the approximation is fairly good. To estimate this relation, we took stellar evolution isochrones by Girardi et al. (2000), and weighted each by its age (thus, in effect, assuming a constant star formation rate), with five isochrones covering ages between 63 Myr and 4.5 Gyr. We then smoothed the resulting distribution of masses in $\log(T_{\text{eff}})\log(g)$ space to yield typical masses at each point.

Having adopted the $BC_r(T_{\text{eff}}, \log(g))$ and $M(T_{\text{eff}}, \log(g))$ relationships, we saw that at the same level of consistency,
several other useful parameters of stars could also be treated as being functions only of \(T_{\text{eff}}\) and \(\log(g)\). These included the luminosity \(L\), the \(V-r\) color (used in relating extinction to distance), and absolute magnitudes in \(V\) and \(r\) bands. Thus, we precomputed tables for all of these quantities, and interpolated into the tables as necessary to give values for any of these quantities as functions of \(T_{\text{eff}}\) and \(\log(g)\).

The process of computing a goodness-of-fit statistic for an individual star then proceeded as follows. We first fetched the observed colors, the \(r\) magnitude, and the galactic latitude \(b\) for each star. We then performed a straightforward (i.e., not particularly efficient) search in \(\{T_{\text{eff}}, \log(g), \log(Z)\}\), seeking the minimum value of a merit function that is the sum of a \(\chi^2\) statistic based on the photometry and the negative logarithm of a prior probability. This section describes the \(\chi^2\) computation; the justification for this general Bayesian procedure and the computation of the prior probability distribution will be described below. The search for the minimum involved evaluating the merit function on successive two-dimensional subsets of the search space; for practical purposes this meant evaluating model colors for a grid of models, each with specified \(T_{\text{eff}}, \log(g), \log(Z)\), and each relating to a star with a specified \(r\) magnitude and galactic latitude. We did this by using an interpolated table lookup to give \(L, B, C, V-r\) from \(T_{\text{eff}}\) and \(\log(g)\), and then computing the distance \(d\) and extinction from \(r, b\), and the galactic extinction model. We then generated model colors for each \(T_{\text{eff}}, \log(g), \log(Z)\) in the current grid of interest, and, knowing the extinction for each of these, applied a corresponding reddening correction to the model colors. Last, we differenced the observed and model colors, and (using the estimated observational errors) computed a \(\chi^2\) value for each grid point.

For some stars, not all of the \(g, r, i, z, D51\) data were available. In these cases, we set the uncertainty for the missing data to \(10^5\) magnitudes, assuring that the actual values made no contribution to the fit.

8. BAYESIAN POSTERIOR PROBABILITY ESTIMATION

When fitting stellar parameters to our photometric data, we found that pure \(\chi^2\) minimization often led to unreasonable results. This is because outlandish combinations of the stellar parameters, corresponding to stars that are seldom or never seen in nature, may yield marginally better fits to the observations than do more plausible parameter combinations.

Bayesian methods provide a way to control this behavior. To describe the application of Bayes’ Theorem to the stellar classification problem, we denote the intrinsic stellar parameters \(\{T_{\text{eff}}, \log(g), \log(Z)\}\) by the vector \(x\), and the various photometric observations of a particular star by the vector \(q\). We assume that we know something about the statistical distribution of stars, so that it is meaningful to talk about the prior probability distribution \(P_0(x)\), where the probability that a given star lies within a small volume of parameter space is given by \(P_0(x)dx\). Then Bayes’ Theorem says that if we add to this a priori information about stars a set of observations \(q\) relating to a particular star, then the updated (posterior) probabilities are

\[
P(x|q) = \frac{P_0(x)P(q|x)}{P_0(q)}.
\]

The choice of stellar parameters that maximizes the posterior probability is then the choice of \(x\) that maximizes this expression. Here the denominator, the a priori probability of observing photometric indices given by \(q\), is a normalization that does not depend upon the parameters \(x\) of interest; for purposes of maximizing the posterior probability, it may be ignored. In the ideal case of independent Gaussian errors in the photometric observations, one can write

\[
P(q|x) = \exp(-\chi^2/2),
\]

where \(\chi^2\) (not the reduced \(\chi^2\)) is the usual goodness-of-fit statistic. Taking the logarithm of the posterior probability, it follows that maximizing this probability is equivalent to maximizing

\[
\ln P(x|q) = \ln P_0(x) - \chi^2/2.
\]

This is what the stellar parameter-estimation procedures try to do.

It is well known that Bayesian methods have both advantages and disadvantages. In the current case one advantage is that wildly implausible stellar classifications are ruled out a priori; the emerging values of \(\{T_{\text{eff}}, \log(g), \log(Z)\}\) are guaranteed to resemble those of known kinds of stars. The corresponding disadvantage is that stars with rare properties are almost certain to be misclassified, since such stars are represented insignificantly or not at all in the statistical samples that one uses to estimate \(P_0(x)\). The Bayesian maximization places stars in the most plausible of the already-existing pigeonholes; if the data are poor or contradict expectations for known kinds of objects, incorrect classifications may occur.

Thus, for the principal Kepler purpose of distinguishing GKM-type dwarfs from giants, the Bayesian approach can be expected to work well. For other purposes (identifying possible brown dwarfs, say, or distant highly reddened blue supergiants), it is better to rely directly on the photometry, and ignore the classifications.

Another problem with Bayesian estimation is that commonly there is no good basis for estimating prior probabilities. Fortunately, in the case of stellar classification, one can do rather well. For purposes of the KIC classification, we expressed \(P_0(x)\) as the product of three terms:

\[
P_0(x) = P_{\text{CMD}}[T_{\text{eff}}, \log(g)]P_z[\log(Z)]P_0(z).
\]

where \(P_{\text{CMD}}\) describes the probability density of stars in the \(T_{\text{eff}}-\log(g)\) plane, and \(P_z\) gives the probability density with height above the galactic plane \(z\). Expressing \(P_0(x)\) as a product distribution implicitly assumes that there are no correlations among the various dependencies. Of course, this is not completely true. Because of the relations between age and \(Z\), and between age and \(z\), the product distribution is not strictly valid. The relatively low frequency of old, low-metallicity stars makes this distribution a reasonable approximation, however. Nevertheless, as we have implemented it, the classification scheme knows nothing of (say) the existence of old low-metallicity halo stars, nor of the absence of young low-metallicity stars, etc.

To estimate \(P_{\text{CMD}}\), we used the Hipparcos (ESA 1997; Hög et al. 2000) catalog to create a histogram of the nearby star distribution, sampled in \((B-V)\)Tycho, \(V_{\text{abs}}\) space. For this purpose we took all the Hipparcos stars with parallaxes that are known to be better than 10%. This sample contained 9590 stars. We then mapped the \(B-V\) color and absolute \(V\) magnitude into \(\log(T_{\text{eff}})\) and \(\log(g)\). Once each star was associated with its calculated \(T_{\text{eff}}\) and \(\log(g)\), it was a simple matter to construct a histogram giving the fraction of stars found within each cell in that space.

After creating the histogram of star frequencies in \(T_{\text{eff}}-\log(g)\) space, we performed several edits and additions to make it more
realistic, complete, and useful. We first set star frequencies to zero for regions where only one or two stars were found in isolated cells. We next added stars to the area of the histogram occupied by bright giants, since the volume covered with good parallax precision by *Hipparcos* is not large enough to populate this part of the diagram. We then scaled the frequencies for intrinsically faint stars to account for the search volume that is implied by the stellar absolute magnitudes, since this volume is determined by the astrometric precision only for relatively bright stars. After doing this, the very faintest M stars were still unrepresented, so we added stars to populate the faint tail of the main sequence. Finally, we smoothed the histogram to yield one that represents the broad features of the local stellar population, but that has little small-scale structure. We took the natural logarithm of this histogram to be the logarithm of population, but that has little small-scale structure. We took the still unrepresented, so we added stars to populate the faint tail of the very faintest M stars were implied by the stellar absolute magnitudes, since this volume is the Hipparcos catalog of detected objects.

For a description of all of the data fields contained in the KIC, see the “Kepler FOV Field Descriptions” page on the MAST/KIC Web site.\(^5\)

10. PHOTOMETRIC DIAGNOSTICS AND VALIDATION OF STELLAR CLASSIFICATIONS

The stellar parameters we assigned to stars were, by construction, distributed in the CMD in plausible ways, and did not conflict with schematic constraints about the spatial and metallicity distribution of stars in the galaxy, but of course these statistical properties of the KIC do not guarantee that individual stars are correctly classified, even though correct classification of individual stars is precisely what the catalog must provide, to serve its purpose. The classifications can fail at many stages in the process. It is hopeless to expect good classifications out of bad photometry, but on many nights the atmospheric conditions were imperfect, or there were problems with the telescope or other instrumentation. Thus, we needed diagnostics of the quality of the photometry, with as much time resolution as we could manage. Also even good photometry can yield poor classifications if there are systematic errors in the models to which the photometry is compared, or if there are true degeneracies in the model-fitting, or if the mathematical model-fitting problem is ill-posed and unduly sensitive to noise. For these reasons it was important to test the classification procedures by comparing their results with independent estimates of the same stellar parameters, obtained from different data sets. There proved to be a number of ways to make such comparisons for restricted sets of stars, and such comparisons have become easier as ground-based observations have been concentrated on the *Kepler* field, and as *Kepler* itself has returned variability information about many target stars. The degree to which the KIC can be validated nevertheless remains rather unsatisfactory; future studies will doubtless give more complete pictures of the successes and failures of the classification scheme. In the following sections, we describe the diagnostics that we used as quality control measures while compiling the KIC, and a few of the validation tests that we have performed.

10.1. Quality of Fits to the Photometry

A simple test of the parameter-fitting process is to compare observed colors for each star with those predicted for the derived stellar parameters \([T_{\text{eff}}, \log(g), \log(Z), E_{B-V}]\). We made plots showing this comparison for each 1-deg-square tile in the *Kepler* field. Within each such tile, we selected stars for which the fit for stellar properties converged, and for which all of the magnitudes \((g, r, i, z, D51, J, H, K)\) had valid values. For each star in this set, we computed model colors. We then formed the difference between the observed colors and the model ones. Each panel of Figure 5 shows the differences plotted as points on a different color–color diagram (e.g., \((r-i)\) versus \((g-r)\), or \((J-K)\) versus \((g-i)\)). The colors were chosen so that every filter is represented at least once. Of interest are the centroids of the plotted clouds of points, their scatter in each color, and the presence or absence of correlations between the residuals in different colors.

For the most part, the fitting process appears to have worked well: for tiles at relatively high galactic latitude (7 deg and above), the residuals have nearly zero mean in all colors, with distributions that are more or less Gaussian. Some colors have more scatter than others—this is the case for any color involving...
Figure 5. Comparison between observed and model colors. This plot represents all of the stars contained in one tile, covering an area spanning 1 deg in R.A. by 1 deg in decl. on the sky near galactic latitude $b \approx 10.5^\circ$. Each point corresponds to one star, and the plotted positions show the residuals (in magnitudes) after subtracting the best-fit model from the photometry for that star, for two chosen colors (e.g., $g-i$ vs. $g-r$, as in panel a). Different panels show various combinations of colors, indicated in the axis labels. The tile plotted here (at R.A. $= 292^\circ$ and decl. $= +40^\circ$) is fairly typical of areas in which the model fits are good. There are several notable features. In panels (a) and (b), the rms scatter in the residuals is 0.02 mag or less in each of $g-r$, $r-i$, and $g-D51$. Errors are anticorrelated between $g-r$ and $g-i$, but this tendency is more noticeable and has a different slope in the wings of the distributions than in the cores. In panels (c) and (d), note the larger scatter (especially in $z-J$), and also the strong negative correlations between these pairs of residuals. In panels (e) and (f), note the change in plot scale; the residuals in the IR colors are much larger than in the visible bands. The $J-K$ and $g-i$ residuals are almost uncorrelated, but one now sees a very significant offset from zero of the mean residual in $g-i$. The two IR colors in the bottom panel have only slightly correlated residuals, but the center of the $J-H$ distribution is also far displaced from zero.

A 2MASS filter or Sloan $z$; evidently the magnitudes in these filters are noisier than in the visible-light filters ($g$, $r$, $i$) by a factor of about two. Also, there are clear anticorrelations between several pairs of colors. Notably, $(r-i)$ and $(i-z)$ are anticorrelated, as are $(i-z)$ and $(z-J)$, and also $(J-H)$ and $(H-K)$. These correlations suggest excess scatter in the common filter of each of $(i, z, H)$. Analysis shows that these anticorrelations arise from two separate processes, one of which affects exclusively the 2MASS magnitudes, while the other is exclusively connected with the visible-light data. Beyond this, the causes of these effects are not yet clear. Tiles at very low galactic latitudes (less than 7 deg) typically show much larger scatter than higher-latitude tiles, and also significant displacement of the mean residuals from zero. We suppose that these effects arise from large and spatially nonuniform interstellar extinction, but as yet we cannot rule out alternative explanations. About 3.3% of the area of the Kepler FOV lies at galactic latitudes of 7 deg or less.

10.2. Giant-dwarf Separation in Color–Color Space

From the perspective of the Kepler mission, the most important task of the KIC is to correctly distinguish giant stars from dwarfs across the greatest possible range of $T_{\text{eff}}$. Figure 6 illustrates the photometric basis for the KIC’s classifications. Panel (a) shows the $(g-D51)$ versus $(g-r)$ color–color diagram for one tile covering 1 deg$^2$ of sky near $b = 10^\circ.5$. 

\[ \text{Figure 6.} \]
Figure 6. Panel (a) shows the \((g - D51)\) vs. \((g - r)\) color–color diagram for the same 1-deg-square tile as shown in the previous figure, at galactic latitude \(b \approx 10.5\). Stars classified as giants (with \(\log(g) < 3.6\)) are indicated by red symbols, and dwarfs (with larger \(\log(g)\)) are plotted as black symbols. Panel (b) is similar to the above, but shows a \((J - K)\) vs. \((g - i)\) color–color diagram for the same tile. The meaning of the symbols is the same.

In both panels of Figure 6, stars classified as giants (defined as having \(\log(g) < 3.6\)) are indicated by heavy red symbols, and dwarfs (with larger \(\log(g)\)) are plotted as small black symbols. In Figure 6(a), main-sequence stars occupy a locus that trends from lower left to upper right as \(T_{\text{eff}}\) falls, until \((g - r) \approx 0.65\) is reached. At this point the \((g - D51)\) colors for dwarfs turn sharply bluerward as \((g - r)\) continues to get redder. At \((g - r) \approx 1.0\) this trend reverses and the \((g - D51)\) color reddens rapidly. The result is that main-sequence stars form a sickle shape: hot stars form the handle of the sickle, and cooler ones form the (curved, concave upward) blade. The area inside the blade of the sickle (and particularly the redward extension of the handle) is occupied by stars with lower surface gravity, or with low metallicity. In these stars the Mg b lines are weak compared to what one sees on the main sequence, resulting in more flux in the D51 band, and a more positive (\(g - D51\)) color.

Figure 6(b) shows \((J - K)\) plotted against \((g - i)\). As is well known (e.g., Bessell & Brett 1988), color–color diagrams involving \((J - K)\) bifurcate for M-type stars, with main-sequence stars limited to \((J - K)\) colors smaller than about 0.9, while low-gravity (and also low metallicity) stars continue to grow redder with lower \(T_{\text{eff}}\). Again, most plots show a clean separation between dwarfs and giants on this diagram, for \((g - i)\) colors that are red enough. Note that both panels of the figure use dereddened colors, where the reddening \(E_{B-V} = A_V/3.1\) is computed from the star’s galactic latitude and estimated distance, as described in Section 7.

10.3. Comparison of Stellar Parameters with Stars in M67

Another useful test of the analysis procedure is to compare fitted parameters for a group of stars with those that can be reliably estimated using other means. One group of stars for which this comparison can be done with confidence is selected from members of the cluster M67. For this cluster D. Latham and S. Meibom provided a list of 116 stars that are thought to be single cluster members. We estimated \(T_{\text{eff}}\) and \(\log(g)\) for these stars from a fit to the Yi et al. (2008) isochrone for solar metallicity and an age of 4 Gyr. Note that M67 lies far outside the Kepler FOV, so these stars do not appear in the KIC proper. Figure 7(a) shows the comparison between \(T_{\text{eff}}\) values for M67 estimated from the KIC and those from a stellar evolution model fit to Montgomery’s \(B, V\) photometry (Montgomery et al. 1993). With the exception of two extreme outlying stars, the
agreement is generally good. The rms difference between the measurements is about 150 K, and the systematic differences appear to be small. Figure 7(b) shows the analogous comparison for \( \log(g) \). Again the general agreement is good, with an rms difference between the isochrone measurements and the KIC fits of about 0.4 dex. Systematic differences are discernible in the difference between the isochrone measurements and the KIC for \( \log(g) \). The most significant of these is a tendency for subgiants identified via isochrone fitting appear as main-sequence stars in the KIC analysis. This is not surprising, since in the \( T_{\text{eff}} \) range where the turnoff to the subgiant branch occurs in M67, none of the filter combinations that were observed for the KIC are sensitive to gravity. The color \( (g - D51) \) shows a useful gravity dependence only for \( (g - r) \) colors greater than 0.65, whereas the main-sequence turnoff in M67 lies at bluer colors, roughly \( (g - r) = 0.38 \).

10.4. Comparisons with Spectroscopic Parameter Estimates

We and others have made comparisons between KIC estimates of stellar parameters and various sets of parameters estimated from modeling of optical spectra. Molenda-Zakowicz et al. (2010) obtained spectra for 109 relatively bright KIC stars, spanning a wide range of \( T_{\text{eff}} \). They found that for temperatures below 7000 K, KIC \( T_{\text{eff}} \) values agree with their spectroscopic estimates within about \( \pm 200 \) K, but that at higher temperatures, larger deviations occur. The largest errors appear for the hottest stars; indeed, in this sample there are nine stars with spectroscopic \( T_{\text{eff}} \) values in the range 9000–13,500 K, and all of these stars are shown in the KIC with lower temperatures, with differences as large as 4000 K. As mentioned above, these failures of temperature estimation are expected for hot stars, because of the absence of \( u \)-band data. Molenda-Zakowicz et al. (2010) found that the KIC surface gravity estimates were fairly accurate for dwarfs, but for giants (including those with \( \log(g) \) as low as 1.5), the KIC estimates could be in error, sometimes by as much as 1.5 dex.

In the process of studying candidate planet host stars, the Kepler mission has obtained high signal-to-noise Keck/HIRES spectra of a few tens of stars, and D. Fischer has analyzed these with the Spectroscopy Made Easy (SME) package (Valenti & Piskunov 1996) to estimate their \( T_{\text{eff}}, \log(g), \) and \([\text{Fe/H}]\). Figure 8(a) shows the comparison for all three parameters for 34 of these stars (all that were available as of 2010 September). The selection criteria for these Kepler planet candidates assured that this sample of stars consists almost entirely of dwarfs with roughly solar \( T_{\text{eff}} \). Thus, the \( T_{\text{eff}} \) range is considerably smaller than for the sample measured by Molenda-Zakowicz et al. (2010). For all but two of these stars, the difference between KIC and HIRES/SME values of \( T_{\text{eff}} \) is 200 K or less; the rms difference is 135 K. There is some evidence for a systematic trend in the \( T_{\text{eff}} \) differences, with the KIC temperatures being cooler than Keck/HIRES at low \( T_{\text{eff}} \) and warmer at high \( T_{\text{eff}} \), but more measurements are needed to confirm this impression. Figure 8(b) compares the KIC and HIRES/SME estimates of \( \log(g) \). Except for one star (spectroscopically classified as a subgiant with \( \log(g) = 3.5 \)), the two sets of estimates agree within \( \pm 0.3 \) dex, and the rms difference is only 0.25 dex. We consider that this agreement is largely artificial, however. The Kepler planetary transit candidates consist almost entirely of stars classified as dwarfs in the KIC, and hence included in the Kepler target list. If these stars are observed to show photometric transit events, then the original classification is likely correct. Thus, for stars selected as these were, we expect at least rough agreement concerning \( \log(g) \). Figure 8(c) compares the KIC and HIRES/SME values of \([Z]\) for the same stars (excluding a few stars in the previous plots for which HIRES/SME values of \([\text{Fe/H}]\) were not reported). The total range of \([\text{Fe/H}]\) estimated by HIRES/SME for these stars is small, about 0.7 dex, and most of the stars are clustered in about half of this range. Accepting (for lack of an alternative) the shortcomings of this sample, one finds that the rms difference between the two sets of estimates is 0.2 dex, and that the Spearman rank correlation coefficient is 0.42, with a two-sided significance of its deviation from zero of 0.02. For comparison, the Spearman statistics for the different \( T_{\text{eff}} \) measurements are 0.96 and 5 \( \times 10^{-17} \), respectively. Thus, while there is evidence that the KIC values of \([Z]\) are related to those measured spectroscopically, the strength of this relationship is unimpressive. Moreover, there appears to be a significant systematic difference between the KIC and HIRES/SME values, in the sense that the KIC \([Z]\) values are about 0.17 dex smaller. We suspect this is symptomatic of the Bayesian prior for \([Z]\) being rather narrowly peaked around \([Z] = -0.1\), whereas planet-bearing stars (which are abundant in this sample) are typically metal-rich (e.g., Fischer & Valenti 2005).

The Kepler mission has also observed a much larger sample of stars using relatively low signal-to-noise ratio spectroscopy (S/N of typically 7–10) obtained from several different sources (McDonald 2.7 m, Mt. Hopkins 1.5 m, Lick 3 m, and Nordic Optical Telescope 2.5 m telescopes). These spectra were obtained to facilitate identification of stellar binaries and to provide crude spectral classifications, so as to make an early decision about the likely origin of apparent photometric transit signals. These “reconnaissance” spectra were analyzed by correlating them against templates created from stellar atmosphere models, using a grid spacing of 250 K in \( T_{\text{eff}} \) and 0.5 dex in \( \log(g) \), and assuming solar metallicity. The stars in this sample were commonly observed spectroscopically two or three times each. Again, by virtue of being selected as transiting planet candidates, these stars form a biased sample, favoring dwarfs. In Figure 9, we plot the average (over observations) of the \( T_{\text{eff}} \) and \( \log(g) \) values estimated for each star against the similar values found in the KIC.

The agreement between KIC classifications and the ones from reconnaissance spectroscopy are worse than for the Keck/HIRES/SME classifications, with random \( T_{\text{eff}} \) differences of about 360 K rms, random \( \log(g) \) differences of roughly 0.3 dex, and evidence for systematic errors of similar magnitude. On the other hand, comparisons between successive spectroscopic estimates of \( T_{\text{eff}} \) and \( \log(g) \) for any given star show scatter of similar size. Thus, a substantial fraction of the scatter in Figure 9 likely results from errors in the spectroscopic reconnaissance measurements. Improved analysis techniques for reconnaissance spectroscopy will soon provide better material for assessing errors in the KIC. In the meantime, we find that KIC \( T_{\text{eff}} \) and \( \log(g) \) estimates agree with those from reconnaissance spectroscopy about as well as the latter agree with each other.

10.5. Comparisons with Asteroseismic Parameter Estimates

Many stars with KIC classifications have been observed to oscillate in global modes, usually \( p \)-modes. Indeed, early Kepler observations are the source of the vast majority of these pulsation detections.

In a simple test, Koch et al. (2010) compared the rms photometric variability of 1000 stars with \( T_{\text{eff}} \leq 5400 \) K, that the KIC classifies as giants, with an equal number classified as dwarfs. Giants are known to be systematically more variable, because virtually all of them show \( p \)-mode oscillations with
amplitudes that increase with increasing stellar luminosity. In these samples, about 2.5% of the stars classified as dwarfs showed variability consistent with their being giants, and none of those classified as giants had variability consistent with dwarfs. It thus appears that, averaged over this sample, the KIC is more than 98% successful in its principal aim—to distinguish between cool giant and dwarf stars.

Detailed seismic analyses have been published for a few Sun-like dwarfs in the Kepler field. Christensen-Dalsgaard et al. (2010) used Kepler time series to search for $p$-mode frequencies and estimate stellar parameters in three Kepler-field stars that were known from ground-based observations to host transiting planets. All of these stars (HAT-P-7, HAT-P-11, and TrES-2), however, are too bright to avoid saturation in the SCP photometry, hence have no $T_{\text{eff}}$ or log($g$) values in the KIC. Chaplin et al. (2010) analyzed Kepler time series for three fainter Sun-like stars, namely KIC 6603624, 3656476, 11026764. The analysis included ground-based high-resolution spectroscopy (allowing estimates of $T_{\text{eff}}$, log($g$), and log($Z$)), and $p$-mode fitting, which when combined with the non-seismic data, allowed estimates of the stellar mass and radius. For these stars, the KIC estimates of $T_{\text{eff}}$ were lower than the spectroscopic ones, by $\{-374$ K, $-242$ K, $-138$ K$\}$, respectively. The KIC estimates of log($g$) were all larger than the seismic estimates, by
(0.064, 0.253, 0.066) dex, respectively. Metcalfe et al. (2010) did an independent analysis of KIC 11026764, finding $T_{\text{eff}}$ and $\log(g)$ values that are consistent with those by Chaplin et al. (2010).

Early Kepler data have revealed long-lived $p$-modes in a large number of giant stars. A recent study by Hekker et al. (2011) has made an explicit comparison between KIC and asteroseismic estimates of $\log(g)$ for a sample of 11,805 stars classified as giants in the KIC that also have Quarter-0 and Quarter-1 Kepler time series available to the public, and in which $p$-modes have been detected. These authors used the method described by Kallinger et al. (2010) to estimate stellar masses and radii from the $p$-mode large frequency separation $\Delta \nu$, the frequency of maximum power $\nu_{\text{max}}$, and the KIC estimate of $T_{\text{eff}}$. This comparison shows that while the KIC correctly ascribes low surface gravities ($\log(g) \leq 3.8$) to almost all of these stars, the KIC values are systematically too large relative to the asteroseismic ones. The magnitude of this error is larger for lower gravities; for clump giants, with $2.3 \leq \log(g) \leq 2.7$, it is about 0.5 dex. The KIC values also show larger scatter at given $T_{\text{eff}}$ than do the asteroseismic ones.

10.6. Comparison with Hipparcos Parallaxes

For a small sample of stars, one may usefully compare the distances inferred from the KIC analysis with parallaxes measured by the Hipparcos mission (Høg et al. 2000). As described in Section 7, the distance $d$ to an observed star is implied by its apparent $r$ magnitude, its galactic latitude, and the exponential model that we use for interstellar extinction. The distance $d$ is not tabulated in the KIC, but it may be computed from the (tabulated) $V$-band extinction $A_V$ as

$$d = -\frac{h}{\sin b} \ln \left(1 - A_V \frac{\sin b}{k_V h}\right)$$  \hspace{1cm} (20)$$

where $h$ is the dust scale height (assumed to be 150 pc), $b$ is the galactic latitude, and $k_V$ is the dust opacity in the galactic plane (assumed to be 1 mag pc$^{-1}$).
Unfortunately, stars with reliable (±20%) *Hipparcos* distances tend to be brighter than typical stars with valid (not saturated) SCP photometry. Thus, the number of stars having both 20% accurate *Hipparcos* parallaxes and converged parameter solutions is only 55, and these lie at distances that are considerably smaller than those of typical *Kepler* stars. Figure 10 shows the comparison of parallax versus extinction distances for this sample of stars. These stars span magnitudes 7.88 ≤ r ≤ 10.84, with colors −0.47 ≤ g − r ≤ 0.87, and KIC temperatures 4684 K ≤ T_{\text{eff}} ≤ 10,735 K. The absolute magnitudes we compute for these stars (based on the parallaxes) show that all but two lie on the main sequence. About 65% of these stars have parallax- and extinction-based distances that agree within a factor of 1.7, or ±0.23 dex. Little of this scatter can be attributed to the parallaxes, so this comparison suggests that KIC stellar radii have 1σ errors that are also about 0.2 dex. This is roughly consistent with our previous estimate of 0.4 dex for the typical error in log(g).

Figure 10 also suggests that (aside from two dramatic outliers) the extinction distances are systematically too small. For this sample of stars, the median distance error is −0.12 dex, or a factor of 0.76. There are two possible explanations for this bias: the in-plane dust opacity k_V may be overestimated, or the luminosities that we attribute to dwarf stars may be too small. We believe that too-small luminosities are mostly at fault, since this explanation is consistent with our previous conclusion that we tend to overestimate log(g) for dwarfs.

There are also two stars for which the extinction distances are much too large. One of these is a binary G-type dwarf that the KIC evidently misclassified as a giant, giving a distance that is much too large and log(g) that is much too small. The other, HIP93941 = BD+42°3250, is classified by Catanzaro et al. (2010) as a B2 star with weak He lines, and by Østensen et al. (2010) as an sdB star. Thus, its temperature is surely much hotter than the KIC value of 10,735 K, and its parallax yields V_{abs} = 4.4. This stellar class is not represented in the Bayesian prior distribution used in the KIC analysis, and hence the object was misclassified as a more luminous and distant star than it actually is.

### 11. KIC SHORTCOMINGS

As indicated above, the stellar classifications provided in the KIC suffer from several known systematic defects that should be considered when using the catalog. Here we describe (or repeat) the most important of these, explain their source when this is known, and illustrate the problems with samples from the data.

#### 11.1. T_{\text{eff}} Scale

KIC T_{\text{eff}} values have systematic disagreements with other T_{\text{eff}} estimates that apply to the same stars. (Of course, these other estimates also disagree systematically with each other.) For approximately Sun-like stars these disagreements are usually less than 50 K, though in the worst cases they may exceed 200 K. For stars that are distant from the Sun on the CMD, one must be more cautious. The KIC T_{\text{eff}} estimates are untrustworthy for T_{\text{eff}} ≥ 10^4 K, and also for T_{\text{eff}} ≤ 3750 K.

For hot stars (T_{\text{eff}} ≥ 9000 K), the lack of u-band data makes our photometry insensitive to variations in T_{\text{eff}}. Higher temperatures are found in the KIC estimates, but their values should not be trusted. We used a subset of the CK models with a maximum T_{\text{eff}} of 19,000 K; the absence of estimates above this value therefore does not imply the absence of such stars in the sample.

The CK model atmospheres we used covered only T_{\text{eff}} > 3500 K, and we applied ad hoc corrections to the colors for T_{\text{eff}} ≤ 3750 K. Temperatures below the latter value are therefore also questionable (although at fixed composition and gravity, the KIC T_{\text{eff}} is probably at least a monotonic function of the true T_{\text{eff}}).

#### 11.2. Subgiant Gravity

The KIC classifications tend to give log(g) too large for subgiant stars, especially those hotter than about 5400 K. This leads to underestimates of the radii of this subset of stars, typically by factors of 1.5–2.

For temperatures above roughly 5400 K, none of our photometric colors provide information about surface gravity. Accordingly, for hotter temperatures the maximum posterior probability analysis has no basis to choose any log(g) other than the one that is most probable a priori, which corresponds to the center of the main sequence, near log(g) = 4.5. Stars on the giant branch almost all have T_{\text{eff}} small enough so that their gravities can be measured; so the gravities of true giants appear to be estimated with errors of typically about 0.5 dex. But for a significant subset of (mostly hot) stars, the KIC-derived gravities are systematically too large, sometimes by more than 1 dex.

Given the available photometric data, this problem is essentially unavoidable. The information needed to distinguish between F- and early G-type dwarfs and subgiants is not present in the photometry, and there is no way to obtain sensible results without it. (Biasing the prior probabilities toward lower gravities, for instance, results in more subgiants, but with no guarantee that the new alleged subgiants are in fact the stars with low gravity.) Users should thus be wary of log(g) estimates for (g − r) ≤ 0.65.

#### 11.3. High log(Z) at Low T_{\text{eff}}

We could perform few tests of the veracity of the estimates of log(Z), and (given the absence of u-band magnitudes) there is little reason to trust these estimates. The (g − D51) color contains...
information about \([Z]\), but this is almost entirely degenerate with the larger and more common color perturbation caused by surface gravity.

A plot of \(\log(Z)\) versus \(\log(T_{\text{eff}})\) for a large randomly sampled group of stars (Figure 11) shows a number of peculiarities. For \(T_{\text{eff}}\) below about 4200 K \((\log(T_{\text{eff}}) = 3.623)\), the estimated \(\log(Z)\) distribution begins to spread and bifurcate, and below 3800 K \((\log(T_{\text{eff}}) = 3.580)\), virtually all stars show \(\log(Z)\) greater than +0.5, which is the highest metallicity represented in the CK models that we use. This behavior has not been investigated in detail, but it seems likely that it results from a mismatch between the model and observed color dependences at low temperatures, in the sense that (other astrophysical evidence notwithstanding), high-metallicity stars provide the best fit to the observations.

One can also observe clustering of \(\log(Z)\) around integral and half-integral values of \(\log(T_{\text{eff}})\), for \(\log(Z) \leq -1\). These are the tabulated values of \(\log(Z)\); the concentration of estimated values near the tabulated ones presumably indicates a failure of the interpolation and fitting code that optimizes the posterior probability.

The most encouraging demonstration that the estimates are doing something sensible was provided by the classifications of stars in the globular clusters M13 and M92. These clusters showed a fairly large (but by no means dominant) fraction of low-\(Z\) star classifications. Based on their positions in our observed cluster CMDs, all of these cluster stars were, however, cool giants, for which we suspect the model colors are particularly uncertain. Thus, whether the classifications for metallicity are performing properly for main-sequence stars is unknown at present; it would be prudent to assume that they are not. Fortunately, the fraction of low-metallicity stars in the solar neighborhood is quite small, so for the purposes of the Kepler mission the uncertainty about \(\log(Z)\) is tolerable, but anyone with a particular interest in stellar metallicities should not use the KIC for their estimates of \(\log(Z)\).

### 11.4. Extinction and Reddening

Regions at low galactic latitude are prone to have large and spatially nonuniform extinction and reddening. The model of extinction that is employed in the Bayesian posterior probability maximization contains no small-scale structure, so it is unable to deal properly with localized large deviations from the mean extinction. the result is systematic misclassification of many stars, a scattered and confused relation between \(T_{\text{eff}}\) and color, and other failings. Examples of such difficulties are shown in Figure 12, which compares tiles at low and high galactic latitudes.

### 12. SUMMARY AND CONCLUSIONS

The KIC is available via the MAST archive facility, operated by the Space Telescope Science Institute.

Experience with the KIC, combined with the testing that we report here and that has been done elsewhere, shows that the KIC has succeeded in its primary goal—to distinguish between cool giant and dwarf stars with good reliability, so that the Kepler mission can select optimum targets for its transiting-planet search. As a by-product of that goal, the KIC provides photometry in the SDSS-like photometric bands \(g, r, i, z\) and in the intermediate-bandwidth \(D51\) bandpass, calibrated with a typical flux accuracy of about 2\%, for stars brighter than about magnitude 14 in any of our filters. All of this information is federated with that from other key photometric and astrometric databases, so that the KIC can serve as a tool for research on

6 http://archive.stsci.edu/kepler/kic10/search.php
a great number of objects that will not be observed by Kepler itself.

Experience and testing has also shown that the KIC has defects. The most notable of these include stars that appear in other catalogs but that have no physical classifications in the KIC, systematic errors in estimates of $T_{\text{eff}}$ for hot and for very cool stars, systematic errors in estimates of $\log(g)$ for stars with $g-r$ colors that are bluer than about 0.65, and questionable metallicity determinations across the CMD. Most of these problems arise from a common cause, namely lack of information about the desired physics in the mostly wide-band photometry that we were able to obtain. By combining $u$-band, and perhaps also suitable intermediate-bandwidth observations with the techniques described here, it should be possible to extend greatly the $T_{\text{eff}}$ range over which the KIC parameter estimates are reliable, and to improve substantially the KIC’s metallicity sensitivity. Also, careful spectroscopic observations of stars that have KIC classifications should allow better characterization of the KIC’s systematic errors. We hope that others will find it useful to provide these improvements.

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