A Search for Candidate Li-rich Giant Stars in SDSS DR10

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Abstract

We report the results of a search for candidate Li-rich giants among 569,738 stars of the SDSS DR10 data set. With small variations, our approach is based on that taken in an earlier search for extremely metal-poor/carbon-enhanced metal-poor stars and uses the same data set. As part of our investigation, we demonstrate a method for separating post-main-sequence and main-sequence stars cooler than \(T_{\text{eff}} \approx 5800\) K using our feature strength measures of the Sr II 4078, Fe I 4072, and Ca I 4227 lines. By taking carefully selected cuts in a multi-dimensional phase space, we isolate a sample of potential Li-rich giant stars. From these, using detailed comparison with dwarf and giant MILES stars, and our own individual spectral classifications, we identify a set of high likelihood candidate Li-rich giant stars. We offer these for further study to promote an understanding of these enigmatic objects.

Key words: methods: data analysis – stars: chemically peculiar – surveys – techniques: spectroscopic

1. Introduction

The many aspects of the evolution of the Li abundance from the Big Bang to the present has generated a very large and complex literature. The existence of Li-rich giants, first discovered by Wallerstein & Sneden (1982), is one part of the Li story. The origin of these unexpected stars is still not fully understood. Here we outline the main points needed to appreciate the strangeness of Li-enriched post-main-sequence (post-MS) stars. For those desiring a deeper review, we recommend the useful and detailed summaries of the observed and predicted post-MS evolution of the Li abundance given by Brown et al. (1989), Ruchti et al. (2011), Casey et al. (2016), and the references cited therein.

The maximum Li abundances of F- and G-main-sequence (MS) stars range from \(A(\text{Li}) \approx 2.1\) for ancient, low-metallicity stars all the way up to \(A(\text{Li}) \approx 3.3\) for young, metal-rich stars (Lambert & Reddy 2004; Prantzos et al. 2017). The Li abundance is expected to change dramatically once stars leave the main sequence. Classical stellar evolution theory predicts that the Li abundance will monotonically decrease once the bottom of the outer convective envelope begins to move inward during post-MS evolution. As the envelope deepens, it increasingly entrains mass zones where complete Li destruction has occurred. This in turn dilutes the MS surface abundance of Li. By the time a star reaches the base of the giant branch, the Li abundance is expected to be only \(\approx 5\%\sim 10\%\) of its MS value (Iben 1967a, 1967b). As the star ascends the giant branch in the classical models, the convective envelope continues to deepen and the Li abundances are predicted to drop even further. Moreover, observational evidence (e.g., Brown et al. 1989; Mallik 1999; Liu et al. 2014) indicates that the actual Li depletion is substantially greater than the classical models predict for the majority of G and K giants.

With this background, it was a great surprise when Wallerstein & Sneden (1982) reported the discovery of a metal-rich, field K giant, HD 112127, whose Li I 6708 resonance doublet line had an equivalent width of 0.44 Å. A model atmosphere abundance analysis of the weaker Li I 6104 transition led to \(A(\text{Li}) \approx 3.0\), very substantially higher than expected theoretically. Kraft et al. (1999) reported the first Li-rich giant in a globular cluster, a star on the first ascent of the giant branch in M3, with \(A(\text{Li}) \approx 3.0\) and a Li I 6708 equivalent width of 0.52 Å. Over the years, other Li-rich giants have been found, both in Population I and Population II. These stars are quite rare however, comprising \(\lesssim1\%\) of giant stars (Brown et al. 1989; Ruchti et al. 2011; Liu et al. 2014; Kirby et al. 2016). The recent tabulation by Casey et al. (2016) lists only 127 known giant stars with \(A(\text{Li}) > 2.0\); the values of \(A(\text{Li})\) in this listing range all the way up to \(A(\text{Li}) = 4.55\). The temperatures of these known Li-rich evolved stars span a considerable range: the hottest is HD 172481, an F supergiant with \(T_{\text{eff}} \approx 7250\) K (Reyniers & Van Winckel 2001) and the coolest is IRAS 12556-7731, an M giant with \(T_{\text{eff}} \approx 3460\) K (Alcalá et al. 2011). Most known examples, however, are found among the G and K stars where our search is optimized.

Numerous hypotheses have been put forward to explain these rare Li-rich giants. The majority appeal to some form of “extra” stellar mixing on the giant or asymptotic giant branches that manages to incorporate the Cameron-Fowler process (Cameron & Fowler 1971) to generate \(^3\)Li. Other scenarios rely on acquiring Li-rich material from a companion. The reader is referred to Kirby et al. (2016) for a brief but insightful review of all these mechanisms.

There is a need to find as many of these rare stars as possible to get the full parameter space describing their occurrence and begin to narrow down the numerous possibilities for producing them. One of the most successful efforts in finding new Li-rich giants was that undertaken by Martell & Schetrone (2013, hereafter M&S13). They searched the Sloan Digital Sky Survey Data Release 7 (SDSS DR7; Abazajian et al. 2009) stars for candidates and identified 27 new Li-rich giants, 23 of which they then subjected to high-resolution abundance analysis. It is the purpose of the current paper to find additional Li-rich giant candidates by carrying out a search using the data of SDSS DR10 (Ahn et al. 2014). The DR10 data set of optical stellar spectra is roughly 1.6X larger than that of the DR7 data.
set. This means that there are a substantial number of additional stars now available to examine for Li-enhancement. We carry out our investigation using a slight variation of the approach we employed earlier in a search for extremely metal-poor (EMP) stars (Carbon et al. 2017, hereafter CHN17).

In Section 2, we briefly describe how we processed the DR10 data set through our reduction pipeline so that we could extract the individual feature measurements that are the basis of our approach. In the sub-sections of Section 3, we detail how we chose our initial Li-rich candidates. In particular, we describe how we selected (Section 3.1) and tested (Section 3.2) feature measurements to impose temperature and luminosity constraints, and how we extracted (Section 3.3) a coarse sample of candidate Li-rich post-MS stars using a set of cuts in a multi-dimensional phase space. Next we describe how we refined the sample to select only the most likely candidates (Section 3.4) and then carried out a detailed spectral classification of these stars (Section 3.5). In Section 4, we discuss our final list of candidate post-MS Li-rich giants. Our principal results are summarized in Section 5.

2. The Data Set

In our search for Li-rich giants, we use the previously prepared data set (CHN17) composed of calibrated optical fluxes and associated data for 569,738 unique stellar spectra drawn from SDSS DR10. The associated data includes each star’s coordinates, heliocentric radial velocity, median signal-to-noise ratio (S/N), pixel-by-pixel inverse-variance values, and u, g, r, i, z point-spread function magnitudes (psfMag). The reader is referred to Section 2 of CHN17 for details concerning the selection of the stellar data from the whole SDSS DR10 database, the processing of the stellar fluxes through our data reduction pipeline, and the feature strength measurements that were subsequently made from the spectra. Here, we review briefly only the salient points needed for understanding the arguments in the current paper.

The first step in our pipeline was establishing a continuum for each spectrum. Once the continuum level was established, it was possible to compute quantitative measures for the spectral lines in each spectrum. Two types of feature measures were adopted. The first was $S(\lambda)$, which is the fractional depth relative to the interpolated local continuum of an individual spectral feature at wavelength $\lambda$. The second was $D(\lambda)$, which is the depth of the line at $\lambda_i$ in units of the local noise level in the spectrum as determined from the spectrum’s pixel-by-pixel inverse-variance values. $S(\lambda)$ is a direct measure of the line’s strength while $D(\lambda)$ gives a handy measure for the line’s strength relative to the local noise level. The latter can be particularly helpful when dealing with intrinsically weak lines like the Li i 6708 line central to this paper. Measurements of $S(\lambda)$ and $D(\lambda)$ were made for 1659 spectral features (each with a unique $\lambda$) for all the 569,738 spectra of our data set. This produced the final data set of nearly 2 billion feature measures used in this study.

In the CHN17 study, stars with specific interesting characteristics were isolated from the above SDSS DR10 data set by using linked scatter plot (LSP) tools implemented on the NASA Advanced Supercomputing hyperwall. (See CHN17, Section 1.1 for a detailed description of LSPs and the hyperwall.) For example, by making judiciously selected cuts in successive two-dimensional (2D) phase spaces, CHN17 were able to extract numerous candidate EMP stars from the general data set. Because of its flexibility, the LSP method has powerful explorative capability. For this reason, we used LSPs on the hyperwall to make the initial reconnaissance of the Li-rich giant problem. It quickly became apparent that there were indeed stars with strong Li i 6708 lines in the DR10 data set. However, because the 569,738 spectra of the data set include a very wide range of temperatures, luminosities, and compositions, we needed to determine how to extract candidate Li-rich giants from the rest of the stars. In the next section, we explain how we accomplished this.

3. Extracting the Candidate Li-rich Giants

We require an approach which will effectively separate the relevant post-MS stars from MS stars that may have comparable Li line strengths. The domain of chief interest is that occupied by the late G and K giants. We need to select feature measures, $S(\lambda)$ and $D(\lambda)$, in our data set that can be used to isolate stars in this desired temperature and luminosity range. Note that our approach relies solely on our feature measures. We specifically chose not to employ SDSS-provided quantities such as $T_{\text{eff}}$ and log g simply because of the large errors that can occur in individual values of these quantities (e.g., M&S13, Appendix A). The following subsections detail how we used the feature measures to arrive at a list of Li-rich giant candidates.

3.1. MILES Spectra to Establish Temperature and Luminosity Constraints

Gray & Corbally (2009) note that the Ca i 4227 line progressively strengthens with decreasing temperature in going from G through K spectral types, while the hydrogen lines progressively weaken over the same spectral range. This suggests that $S$(Ca i 4227) or $S$(H i) could be used as a first-order surrogate for stellar temperature. (We note here that we investigated using colors based on the SDSS u, g, r, i, z magnitudes as temperature surrogates but found that they did not lead to clean separation between MS and post-MS stars.) In order to estimate luminosity in G and K star domain, Gray & Corbally (2009) and White et al. (2007) suggest a number of possible metal line strengths and ratios. To determine whether any of these might be helpful in our investigation, we turned to the MILES spectrum library (Sánchez-Blázquez et al. 2006).

The 985 stars in the MILES library were selected for the purposes of stellar population synthesis. As a result, they cover a wide range of temperatures, luminosities, and metallicities with particularly good coverage for the spectral ranges of most interest to us (e.g., Sánchez-Blázquez et al. 2006, Figure 1). The MILES spectra span the whole SDSS optical wavelength range relevant to our study and have essentially the same spectral resolution as the SDSS spectra. Moreover, the stars in this library have carefully researched $T_{\text{eff}}$, log g, and metallicity ([Fe/H]) drawn from the literature (Cenarro et al. 2007). These attributes make the MILES spectra ideal for determining which luminosity criteria might be most effective for separating G and K MS stars from post-MS stars. To take advantage of the MILES library, we ran the entire data set of nearly 1000 MILES spectra through the same spectral reduction pipeline that we used in our earlier study. The pipeline computed continua for each of the MILES spectra and then computed $S(\lambda)$ and $D(\lambda)$ measures for each of the 1659 spectral features we use. Details of the pipeline process may be found in CHN17, Sections 2.1–2.3.
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To explore which of the Gray–Corbally and White et al. luminosity criteria might be best for our purposes, we extracted two subsets from our full MILES data set of feature measurements. The first subset, which we used to represent MS stars, was comprised of the 344 MILES A through K stars with Cenarro et al. (2007) \( \log g > 3.80 \). The second subset, representing post-MS stars, was comprised of the 254 MILES A through K stars with Cenarro et al. (2007) \( \log g \leq 3.80 \). The division in \( \log g \) was chosen to be comparable to that adopted by M&S13 in isolating post-MS stars for their study.

Many of the Gray–Corbally and White et al. luminosity criteria in the G–K spectral range are ratios of lines strengths (or sums of line strengths), e.g., the ratio of Y II 4375 to Fe I 4384. We represented these by taking the ratios of the corresponding line strength measures, as in \( S(Y \, \text{II} \, 4375) / S(Fe \, I \, 4384) \). Using the MS and post-MS subsets of MILES data, we examined the various luminosity sensitive line ratios versus the feature strengths of the likely temperature sensitive lines: \( S(H_{\alpha}), S(H_{\beta}), S(H_{\gamma}), \) and \( S(Ca \, I \, 4227) \). After considerable experimentation, we found that \( S(Sr \, II \, 4078) / S(Fe \, I \, 4072) \) versus \( S(Ca \, I \, 4227) \) gave the clearest separation between MS and post-MS stars for the G-K stars. We show this separation in Figure 1. The luminosity sensitivity of the \( S(Sr \, II \, 4078) / S(Fe \, I \, 4072) \) ratio is a result of the rather different electron pressure sensitivities of these two lines in the cooler stars. The line ratio systematically shifts as the gravity, and hence electron pressure, decreases with increasing luminosity. A discussion of such effects may be found in Gray (1992), for example.

The locations of the MS and post-MS stars (black and red circles, respectively) in Figure 1, show that, while there are a few exceptions, the \( Sr / Fe \) ratio nicely discriminates between MS and post-MS stars in the region \( S(Ca \, I \, 4227) \geq 0.4 \). In contrast, the \( Sr / Fe \) ratio becomes unreliable as a luminosity diagnostic for \( S(Ca \, I \, 4227) < 0.4 \).

3.2. Comparison with Confirmed Li-rich Giants

It is helpful to illustrate how a known set of Li-rich giants are distributed in Figure 1. M&S13 searched for Li-rich giants among the stars of SDSS DR7. They chose a set of 8535 stars from DR7 whose SEGUE Stellar Parameter Pipeline (SSPP) \( T_{\text{eff}} \) and \( \log g \) values indicated that they would be red giant branch (RGB) stars lying somewhere between slightly below the red giant bump and the red giant tip. They estimated the Li 6708 strength in these stars using a spectral index they computed centered on the line. Selecting only those stars with the most promising Li spectral indices (162 stars), they used low-resolution spectrum synthesis to sub-select a set of 36 for follow-up high-resolution study. Of these 36, they confirmed that 27 were indeed Li-rich based on high-resolution spectroscopy and spectrum synthesis. (We note that M&S13 present derived Li abundances for only 23 of the 27 stars because of S/N problems. Nevertheless, we will consider all 27 as “confirmed Li-rich” as indicated in their Table 1.) Of these 27 SDSS DR7 Li-rich stars, 19 are included in the download for our DR10 data set, the 8 missing stars violated one or more of the selection criteria we adopted in selecting the stars for our data set.

In Figure 1 we show the 19 M&S13 stars as cyan diamonds. We see that 9 of the 19 M&S13 stars fall comfortably in the region occupied by post-MS stars with \( S(Ca \, I \, 4227) \geq 0.4 \). The remainder, with smaller \( S(Ca \, I \, 4227) \) values, have SDSS \( [Fe/H] \) ranging from \(-1.4 \) to \(-2.6 \), i.e., they are metal-poor. The other two stars have the highest \( T_{\text{eff}} \) values (5250 K, 5625 K) of the stars with \( S(Ca \, I \, 4227) < 0.4 \) as well as depressed \( [Fe/H] \) (\( \lesssim -0.29 \)). (The 2 stars that do not have M&S13 \([Fe/H]\) values, have SDSS \([Fe/H]\) of \(-0.66 \) and \(-1.50 \).) Both low metallicity and higher \( T_{\text{eff}} \) could explain the presence of M&S13 stars to the left of the \( S(Ca \, I \, 4227) = 0.4 \) boundary. All of the stars to the right of the \( S(Ca \, I \, 4227) = 0.4 \) boundary have \([Fe/H]\), as determined by M&S13, ranging from \(-0.47 \) to \(+0.41 \). This suggests that, by restricting ourselves to stars with \( S(Ca \, I \, 4227) \geq 0.4 \), we may run the risk of missing Li-rich giants with low metallicities. Because we see no obvious way at this time to devise a luminosity criterion that does not risk excluding such stars, we shall proceed. Low-metallicity giants that are sufficiently cool (hence having intrinsically stronger Ca 4227) might still land to the right of the \( S(Ca \, I \, 4227) = 0.4 \) boundary and thus be detectable by us.

3.3. Imposing the Final Constraints

In order to arrive at a useful set of Li-rich giant candidates, it is necessary to constrain more than just the value of \( S(Li \, i \, 6708) \) and the region in \( S(Fe \, I \, 4072) / S(Fe \, I \, 4072) \) versus \( T_{\text{eff}} \) relation for the MILES stars indicates that the \( S(Ca \, I \, 4227) = 0.4 \) boundary occurs at \( \approx 5800 \) K, a temperature that corresponds to early-mid G stars in the case of dwarfs (Boyajian et al. 2012). Thus, as it places us in the stellar temperature range most relevant to our search, restricting our search to stars with \( S(Ca \, I \, 4227) \geq 0.4 \) should pose no difficulty. However, in the next sub-section, we will note one important caveat.

\[
\text{Figure 1. Selected luminosity indicator, } S(Sr \, II \, 4078) / S(Fe \, I \, 4072), \text{ vs. } S(Ca \, I \, 4227), \text{ a temperature surrogate. The MILES MS stars are plotted as black circles and the post-MS stars as red circles. See the text for details of how the MILES stars were divided according to the criteria in the G–K stars, was comprised of the 344 MILES A through K stars with Cenarro et al. (2007) } \log g > 3.80. \text{ The second subset, representing post-MS stars, was comprised of the 254 MILES A through K stars with Cenarro et al. (2007) } \log g \leq 3.80. \text{ The division in } \log g \text{ was chosen to be comparable to that adopted by M&S13 in isolating post-MS stars for their study.}
\]
versus \( S(Ca \ 4227) \) space. For good quality results, one must also add constraints on the noise levels both overall and locally in the 6700 and 4070 Å regions. Similarly, it is necessary to guard against TiO contamination of the Li I 6708 line region. After considerable experimentation, we chose the set of constraints listed below. The additional constraints eliminated many spectra in which noise/contamination produced uncertain results for the value of \( S(Li \ I \ 6708) \) and/or the \( S(Sr \ II \ 4078)/S(Fe \ I \ 4072) \) ratio.

The measures we selected and the constraints we imposed on them are summarized in the logical expressions below. All of these constraints, 1–6, are applied at the same time to the feature measures of the 569,738 stars in the data set. Only stars that simultaneously satisfy all the specified constraints are considered in the remaining discussion.

\[
\begin{align*}
(0.4 \leq S(Ca \ I \ 4227) < 0.69) \quad \text{and} \quad (S(Sr \ II \ 4078)/S(Fe \ I \ 4072) \geq (2.96 - 2.90 \times S(Ca \ I \ 4227))) \\
(S(Ca \ I \ 4227) \geq 0.69) \quad \text{and} \quad (0.96 < (S(Sr \ II \ 4078)/S(Fe \ I \ 4072)))
\end{align*}
\]

\[
\begin{align*}
S(Li \ I \ 6708) \geq 0.04 \\
\text{median (S/N) > 20} \\
D(Li \ I \ 6708) > 1.0 \\
S(Sr \ II \ 4078) > 0.0 \\
S(TiO \ 6815) < S(Li \ I \ 6708).
\end{align*}
\]

We now briefly describe the rationale for each cut shown above:

Constraints 1(a) and (b) apply the luminosity discriminant ratio \( S(Sr \ II \ 4078)/S(Fe \ I \ 4072) \) described in Section 3.1. Constraint 1(a) applies to the left-hand portion of the region outlined by cyan dashed lines in Figure 1 (i.e., \( 0.4 \leq S(Ca \ I \ 4227) < 0.69 \) and above the sloping cyan dashed line); 1(b) applies to the right-hand portion (i.e., \( S(Ca \ I \ 4227) \geq 0.69 \) and above the horizontal cyan dashed line).

Constraint (2) further selects out those stars that have Li I absorption strengths above a minimum threshold. We selected the threshold to be equal to the \( S(Li \ I \ 6708) \) measure of the M&S13 Li-rich giant with the weakest Li I feature.

Constraint (3) isolates the objects that have sufficient S/N in their spectra to make estimating luminosity and Li I strength more robust. We found that the spectra of stars with poorer S/N are generally much too noisy to yield reliable measures of either \( S(Sr \ II)/S(Fe \ I) \) or \( S(Li \ I) \).

Constraint (4) further limits the subset of stars to those with Li I 6708 line depths more than 1σ above the local noise level. This helps eliminate stars that have excessive noise near the Li I line.

Constraint (5) limits the stars to only those with detected Sr II 4078 absorption, removing stars for which random noise, or poor continuum placement, produces a false emission feature.

Constraint (6), which uses a \(^{48}\text{Ti}^{16}\text{O} \) (3, 2) gamma system band head, was introduced to bias against stars for which the TiO bands were becoming sufficiently strong that they were noticeably affecting the region of the Li I line.

To impose the constraints described above, we constructed a suite of MATLAB\textsuperscript{®} (MATLAB 2011) codes implemented on a single computer workstation. The suite reads in the constraints on specified feature variables and returns a list of those stars for which the specified variables simultaneously satisfy all the constraints. This is logically equivalent to the CHN17 method of making a series of successive cuts in 2D phase spaces that was the basis of the LSP approach. Applying the constraints 1 through 6 to the data set of 569,738 SDSS DR10 stars produces a subset of 1523 stars, which are potentially Li-rich giants. In the next sub-section, we will describe how we select out the most likely candidate Li-rich giants.

### 3.4. Extracting the Candidate Li-rich Giants

#### 3.4.1. Eliminating the Obvious False Positives

The feature constraint on median S/N in Equation (3) was intentionally left “softer” than it might have been so as to capture as many candidates as possible. However, this means that stars may slip through the constraints whose spectra are too contaminated by noise in crucial spectral regions to be sure of their status. In addition, some of the feature strengths used in the constraints may have erroneous values caused by poor continuum placement. (A more detailed discussion of these issues may be found in CHN17, Section 4.) We dealt with these issues by visually examining the spectra of each of the 1523 stars selected by the constraints of the previous section. The visual examination was done in two steps.

In the first step, the chief criteria were the strength and apparent position of the purported Li I line, whether the spectral regions around Li I line and the luminosity indicators appeared relatively unaffected by noise, whether there appeared to be TiO contamination of the Li region, and whether the continuum placement was appropriate. A secondary consideration was whether the Li I 6708 line was comparable to or stronger than Ca I 4227 (see Casey et al. (2016, Figure 5)). The ratio of these two lines was used by Kumar et al. (2011) in their study to identify candidate Li-rich stars from low-resolution giant spectra. This coarse initial cull was straightforward and was accomplished relatively quickly. It eliminated 1350 stars from further consideration, the vast majority because the local noise level was too large to be confident of the Li I line strength.

In the second step, the spectra of the 173 remaining stars were subjected to a more prolonged and careful visual inspection, which concentrated on the position, shape, and strength of their Li I 6708 line and the quality of the spectrum. Stars were eliminated if the apparent Li I feature appeared to be strongly asymmetric, shifted significantly from its nominal position, or was too similar in appearance to the surrounding noise features. This second visual cull left 49 candidates. These 49 stars included all 9 of the M&S13 Li-rich giants that fell into our search region, evidence that our selection procedure was working well. The next sub-sections describe how we confirmed whether the final 40 previously unrecognized Li-rich candidates were indeed giants.

#### 3.4.2. Comparison with MILES Stars

To increase our confidence in the likelihood that we were selecting stars that were good Li-rich giant candidates, we first carried out a systematic comparison of each of the 40 stars with the MILES MS and post-MS stars. First we normalized the spectrum of each Li-rich giant candidate and each MILES MS and post-MS star. This was accomplished by normalizing each spectrum by its continuum and then by its flux at 5837 Å so as to keep the scales of the different spectra consistent. Next we interpolated the resulting MILES spectra onto the SDSS DR10
wavelength set over the interval \([3850–7400 \,\text{Å}]\). Using the resulting fluxes, we computed the following summed square differences, SSD, for each of the 40 stars against each of the spectra of all the MILES MS stars seriatim and then, separately, all the MILES post-MS stars:

\[
SSD = \sum_{k=1}^{n} \left( F_{\text{cand}}(\lambda_k) - F_{\text{MILES}}(\lambda_k) \right)^2,
\]

where \(F_{\text{cand}}(\lambda_k)\) is the normalized flux at wavelength \(\lambda_k\) of one of the candidate Li-rich stars, \(F_{\text{MILES}}(\lambda_k)\) is the corresponding normalized flux of one of the MILES stars, and \(n\) is the number of wavelengths in the common wavelength set.

For each candidate Li-rich star, we compared its spectrum with the closest matching (i.e., smallest SSD values) MILES MS and post-MS stars to see whether the candidate spectrum appeared more consistent with the spectra of dwarfs or giants. Attention was paid not only to the Sr II 4078/Fe I 4072 ratio, but also to the strengths of Sr II 4078 relative to the Fe I 4064 and Fe I 4046 lines (Gray & Corbally 2009). We also considered the values of SSD for the candidate star and the ten closest matches from the MILES main-sequence and post-MS lists. For many stars, the SSD values for the top ten closest matches were very strongly in favor of a candidate being most like a giant or dwarf.

Based on the above comparisons, 31 stars were rejected because they more closely matched the spectra of MILES MS stars both in their Sr II to Fe I line ratios and in their SSD values. Nine stars remained as candidates to be Li-rich giants. We decided it was prudent to subject these nine stars to an additional final check. The next sub-section describes the effort by one of us (ROG) to examine the spectra of the nine stars in detail and make definitive spectral type classifications based on more than the limited number of spectral features we have considered up to this point.

3.5. Detailed Spectral Classification

While the SDSS spectra have a much larger spectral range, the most sensitive temperature and luminosity criteria are found in the violet—green region, 3800–5600 A. Because of the unavailability of an MK standard star library for the SDSS spectra, we convolved the SDSS spectra with a Gaussian to reduce the resolution to that of the \texttt{libnor36} MK Standards library\(^4\) (3.6 Å/2 pixels) of Gray & Corbally (2014).

Gray & Corbally (2009) detail the temperature and luminosity criteria used in the MK classification of G- and K-type stars. In summary, temperature criteria involve the ratio of low-excitation neutral metal lines to hydrogen lines (Fe I \(\lambda\lambda 4046/\gamma H,\) Fe I \(\lambda\lambda 4144/\gamma H,\) Fe I \(\lambda 4383/H\gamma\)) as well as similar line ratios in the vicinity of Hβ. Those ratios, however, are invalid in metal-poor stars, and in that case, the ratio of lines of the Cr I triplet (\(\lambda\lambda 4254, 4275, 4290\)—all resonance transitions) with the higher-excitation Fe I \(\lambda\lambda 4250, 4260,\) and 4326 lines provide metallicity-independent temperature criteria. Luminosity criteria include the ratios of Sr II \(\lambda\lambda 4077\) to nearby Fe I lines (\(\lambda\lambda 4046, 4064,\) and 4072), Sr II \(\lambda\lambda 4216/Ca I \lambda\lambda 4226,\) Y II \(\lambda 4376/\text{Fe I} \lambda 4383\) as well as the strength of CN violet system, in particular the band bluedward of the \(\lambda 4215\) band head. However, in stars with carbon abundance peculiarities, the CN band strength can give spurious results, as proved to be the case with a number of stars in the candidate Li-rich sample under consideration.

The spectral types were determined by eye on the computer screen by direct comparison with the \texttt{libnor36} MK standards. The spectral types we obtained are listed in Table 1 for the eight candidates that proved to be giants. One candidate (J215914.37+004515.8) turned out to be a G9 dwarf and will not be considered further. Three out of the final eight appear to be normal late G- and early K-type giants. The remaining stars, all late G- to early K-type giants (with the exception of J150029.54+010744.8, which is a Ib-II supergiant), show carbon peculiarities in the form of weak CH (G-band) and CN bands.

4. Results

The final set of eight stars that survived the vetting process described in the previous section are presented in Table 1. For completeness, we retain J150029.54+010744.8 in the set of candidates despite its luminosity class. A model atmosphere analysis will be needed to accurately place it relative to the giant branch. The table gives the date of observation of the measured SDSS DR10 spectrum, selected feature strengths and ratios as described in the text, the SDSS-assigned spectral type, and the spectral type determined by us. The \(S(\text{Li} 6708)\) values show that, despite the comparatively low resolution of the SDSS spectra, the absorption depths of the Li I lines in the candidates are not trivial, ranging from 5% to 17%. The \(D(\text{Li} 6708)\) values, the line depth in units of the local noise level, all suggest solid detections. Comparing the two columns of spectral types in the table, it is immediately apparent that our spectral types are all systematically earlier than the SDSS assignments. The differences are generally small and perhaps partially reflect the coarseness of the ELODIE library used by SDSS to classify the stars (Lee et al. 2008). Nuances introduced by weakening of CH and CN bands within a spectral type, captured by our approach and indicated in the “SpT Notes” column, might have confused the SDSS classification as well.

The DR7 data set used by M&S13 contains observations obtained up to 2008 July (Abazajian et al. 2009), whereas the DR10 data set we used contains SDSS optical observations through 2012 June (Ahn et al. 2014). As we mentioned in Section 3.4.1, our approach captures all nine M&S13 stars in our data set that have \(S(\text{Ca I} 4227) \geq 0.4\). We note that Table 1 contains four additional stars that, according to their dates of observation, were present in the DR7 data set. These stars apparently failed to pass one of the selection criteria used by M&S13 to derive their list of 36 Li-rich candidates suitable for high-resolution examination. It will be interesting to see whether or not future analysis of these stars confirms that they are Li-rich giants as we suggest. The spectra of the remaining four stars in Table 1 were obtained after 2008 July and could not have been considered by M&S13. We find it somewhat surprising that we discovered only four new candidates among the stars observed after the end of the DR7 data set. Our downloaded CHN17 data set has 364,265 stars observed before 2008 July and 205,473 stars observed after that date. This makes the 2008 post-July portion of the data set 56% of the size of the earlier portion. Given that we found a total of 13 Li-rich

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\(^4\) That library, as well as other MK standards libraries may be downloaded as ascii files (mklib.tar.gz) from \url{http://www.appstate.edu/~grayro/mkclass/}. The MK standards used in \texttt{libnor36} are listed on that same site.

\(^5\) Note that the wavelengths used in this sub-section are those adopted by Gray & Corbally (2009) and may differ slightly from the air wavelengths used elsewhere in the paper, which are rounded to the nearest Å.
candidates in the earlier data set (the 9 M&S13 stars plus our 4 new candidates), one naively might expect that the more recent portion alone would yield roughly 7 candidate Li-rich giants. That we found only four may be only a reflection of the uncertainty of small number statistics. It also may be the result of a shift in the spectral type mix between the two portions of the data set given that the stellar classes targeted by the SDSS changed with time as the survey went on.

We show in Figure 2 spectra of the stars of Table 1 in the vicinity of the Li I line. We have marked with dashed lines the Li I 6708 doublet, the Ca I 6718 feature used by Kumar et al. (2011) and used by us as a secondary criterion, and the TiO 6815 band head we used in Section 3.3. For comparison, we also show at the bottom the two high S/N M&S13 stars with S(Ca I 4227) $\geq$ 0.4 having the weakest and the strongest Li I lines. It is apparent that the Li I features in our candidates are comparable in strength or stronger than those in stars identified as Li-rich giants by M&S13.

Finally, we show our Li-rich giant candidates in Figure 1 as green dots. Our eight candidate Li-rich giants are distributed in the plot much like the nine M&S13 already-confirmed Li-rich giants. The most luminous are well away from the boundary between the MS and the post-MS stars. Like the majority of M&S13 stars, the remainder of our candidates lie closer to the boundary. The locations of our candidates in Figure 1, their spectral types in Table 1, and their strong Li I lines (Figure 2) all suggest that they are Li-rich giants. We offer these candidates to researchers for closer examination, an undertaking well beyond the limited scope of this paper. Model atmosphere analyses of higher-resolution spectra will be required to definitely determine the Li abundance and evolutionary status of our candidate Li-rich giants.

5. Summary

In the current paper, we describe a new approach to identifying candidate Li-rich giants using the SDSS DR10 data release. As part of an earlier investigation (CHN17), 569,738 SDSS DR10 spectra were processed through a pipeline that yielded feature strength measurements for each of 1659 unique spectral features in each spectrum. The resulting nearly 2 billion feature measurements can be used to construct phase spaces of measurements. One may then introduce constraints that can be used to isolate stars with desired characteristics.

Table 1

| Star Name          | Obs Date  | S   | D   | Li I | D   | S   | Ca I | Sr II /Fe I | SDSS | SpT   | Our   | SpT   |
|--------------------|-----------|-----|-----|------|-----|-----|------|------------|------|-------|-------|-------|
| J021646.38-003333.5 | 2010 Oct 10 | 0.14 | 10.7 | 0.68 | 1.64 | K4III | K0 III-IV | ...         |      |       |       |       |
| J060724.43-240052.4 | 2008 Feb 25 | 0.08 | 6.7  | 0.54 | 1.55 | K1   | G9 III-IV | ...         |      |       |       |       |
| J062219.56+414403.8 | 2007 Dec 07 | 0.05 | 3.6  | 0.50 | 2.49 | K1   | G8 II-III | ...         |      |       |       |       |
| J092210.66+162455.9 | 2012 Mar 12 | 0.11 | 6.6  | 0.64 | 4.40 | K4III | G9 II-III CN-1 | ... | a       |       |       |
| J122728.00+054420.2 | 2009 Apr 20 | 0.14 | 10.6 | 0.85 | 1.14 | K5   | K0 III CN-1 CH-1 | ... | b       |       |       |
| J143237.11+024533.4 | 2001 Mar 31 | 0.15 | 8.2  | 0.77 | 4.25 | K5   | K0 II-III CN-2 CH-2 | ... | c       |       |       |
| J150029.54+010744.8 | 2009 May 19 | 0.17 | 12.7 | 0.61 | 4.73 | K5   | G8 Ib-II CN-1 | ... | d       |       |       |
| J183259.15+22243.5 | 2006 Jul 01 | 0.11 | 4.1  | 0.57 | 1.43 | K1   | G8 III CN-0.5 | ... | e       |       |       |

Notes.

a) CN band weak.
b) Both CN and CH bands weak.
c) Both CN and CH bands weakly.
d) CN band weak for luminosity type.
e) CN band slightly weak.
Visual inspection of the spectra quickly reduced the list of possible candidates to 49 stars, 9 of which were Li-rich giants already discovered by M&S13. Next, the remaining 40 stars were systematically compared with those MILES dwarf and giant stars most similar to them in overall spectral energy distribution. Stars selected as most compatible with giants were then carefully classified for spectral type. These steps produced the eight candidate Li-rich giants shown in Table 1. We strongly recommend that researchers interested in expanding the list of known Li-rich giants consider these stars for detailed high-resolution investigation.

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