Photometric Separation of Physical Properties of Stars

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ABSTRACT

Photometry collected using Sloan Digital Sky Survey filter systems shows that it is possible to photometrically separate low metallicity stars with $0.5 < g - r < 0.8$ using *ugri* filters, and to separate stars with $-0.2 < (g - r) < 0.25$ by surface gravity using *ugriz* filters. This confirms the result of Lenz et al. 1998, which predicted from Kurucz model atmospheres that for G/K stars there was a relationship between metallicity and the l-parameter, $l = -0.436(u - g) + 0.693(g-r)+0.574(r-i)+0.199$; and for A stars there was a relationship between surface gravity and the v-parameter, $v = 0.283(u - g) - 0.354(g - r) + 0.455(r - i) + 0.766(i - z)$. Photometric metallicities are a rough guide to sort metallicities, but can give very incorrect metallicities for unusual stars such as carbon stars and X-ray sources. The photometric metallicity determinations may make it possible to study the statistics of Galactic populations without time-consuming spectroscopic analysis, thus leveraging our ability to study Galactic structure and abundance gradients in the Galactic halo and thick disk. Application of the l-parameter to tens of millions of Galactic stars in the SDSS catalogs will allow us to select low metallicity candidates for further spectroscopic analysis. This technique is already being used for target selection in SEGUE, which is part of SDSS II, the three year extension to the SDSS.

1. Introduction

The Sloan Digital Sky Survey (SDSS) has already released accurate photometric data for 141 million unique objects, about half of which are Galactic stars, in 5252 square degrees

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of the sky at high Galactic latitudes. Each object includes photometry in the five $ugriz$ filters. By the end of the survey, about 50% more data will be available. Given the large number of stars with photometry available in this new system, it is important to discover what physical parameters of stars these filters can predict.

Lenz et al. (1998) noticed, from convolution of Kurucz models with the predicted transmission curves for the SDSS filters, that the locus of stars in three dimensional color space was largely two dimensional. This means that of the three primary stellar atmospheres parameters – temperature, gravity, and metallicity – at most two could be discovered photometrically. They discovered that for stars with colors $0.5 < g - r < 0.8$ (typically K stars), there existed a combination of colors, $l = -0.436(u-g) + 0.693(g-r) + 0.574(r-i) + 0.199$, that was an indicator of photospheric metallicity.

Additionally, a photometric gravity indicator, v, was proposed for A-type stars with $-0.20 < g - r < 0.25$. The v-parameter is given by $V = 0.283(u - g) - 0.354(g - r) + 0.455(r - i) + 0.766(i - z)$.

In order to run quality assurance tests on the SDSS data, Ivezić et al. (2004) also developed a parameter called the s-parameter, $s = -0.249u + 0.794g - 0.555r + 0.234$, which has been used as an indicator of metallicity. This parameter was also used by Helmi et al. (2003) to select low metallicity giant stars. The s-parameter showed more variation than predicted by photometric errors, and was thus judged to be a measure of some intrinsic stellar property. The Helmi et al. (2003) paper selected stars with $1.1 \leq u-g \leq 2$, $0.3 \leq g-r \leq 0.8$, and $-0.1 \leq 0.910(u - g) + 0.415(g - r) - 1.28 \leq 0.6$. Low metallicity giants were chosen as those stars with $s > m_s + 0.05$, where m_s is the median value of the s color in appropriately chosen subsamples.

The definition of this parameter has been changed slightly to reflect a shift in the definition of the SDSS photometric system. The new definition is: $s' = -0.239u + 0.789g - 0.560r + 0.210$. Unlike the l-parameter, the s'-parameter has a very slight dependence on magnitude. For easier comparison with the l-parameter, $l = -0.436u + 1.129g - 0.119r - 0.574i + 0.199$.

In this paper, we test the l-parameter as a predictor of metallicity for G/K-type stars using SDSS photometry of well-studied, bright metallicity standards.

2. Photometric systems

Lenz et al. (1998) used the $u'g'r'i'z'$ response functions derived by Fukugita et al. (1996)

for the SDSS 0.6m Monitor Telescope (MT), the telescope upon which the SDSS $u'g'r'i'z'$ standard star network was to be defined. However, due to engineering difficulties, the original MT was replaced by the 0.5m Photometric Telescope (PT) (Hogg et al. 2001; Stoughton et al. 2002). While the PT was being commissioned, the $u'g'r'i'z'$ standard star network was established using the US Naval Observatory 1.0m telescope at Flagstaff Station, Arizona. The response curves derived for the USNO-1.0m are very similar to those derived for the original MT, but there were small differences between the predicted filter curves for the *ugriz* system and the filter curves measured after the system was in operation. The main differences are in the response curves that include atmospheric effects (airmass), since Flagstaff Station is at a different altitude than Apache Point Observatory, where the MT was located. The derived response curves for the USNO-1.0m $u'g'r'i'z'$ filters are available online at http://home.fnal.gov/∼dtucker/ugriz/index.html.

Since the SDSS 2.5m telescope has different CCD cameras and different transmission than either the PT or the USNO 1m, there is a separate system defined native to this primary survey telescope, with small transformations between the three photometric systems currently in use in the SDSS. Magnitudes with primes denote the USNO-1.0m system, and magnitudes without primes denote the 2.5m system. At intermediate colors where we are working, all of the transformations between systems should be small, though we worried that there could be some degradation of the accuracy of the Lenz et al. (1998) metallicity vs l-parameter relations due the evolution in our understanding and definition of the system response.

We attempted to measure any offset between the Lenz et al. (1998) predicted colors and the colors on the SDSS 2.5 meter system, to which all magnitudes in this paper have been converted. We did this by measuring the colors of Gunn-Stryker stars for which synthesized magnitudes were already calculated, and by looking for an offset between the predicted and measured colors for stars with measured $T_{\rm eff}$, $\log g$, and [Fe/H].

Three Gunn-Stryker stars were observed with the SDSS PT: HD 191615, HD 113493, and HD 170527. The colors obtained for HD 191615 were offset from the synthetic colors by 0.028, -0.009, 0.038, and 0.008 magnitudes in $u-g$, $g-r$, $r-i$, and $i-z$ respectively. HD 113493 had offsets of 0.026, 0.015, 0.055, and 0.019 magnitudes in $u-g$, $g-r$, $r-i$, and $i-z$ respectively. The third Gunn-Stryker star, HD 170527, was saturated in $r, i, andz$ and was therefore discarded. The small shifts are shown graphically as the large symbols in Figure 1. Though the statistics is derived from very small numbers, there appear to be significant shifts in $u-g$ and $r-i$ of approximately 0.03 and 0.05 magnitudes, respectively. However, application of this correction changes the l-parameter by only -0.005 magnitudes.

We used measurements of metallicity, T_{eff} and log(g) for 29 of our observed stars (see

Section 3), to interpolate the synthetic colors of our observed stars based on those presented in Lenz et al. The difference between the measured and synthetic colors is shown as the smaller symbols in Figure 1. There is a large, asymmetric scatter in the distribution of color offsets, but it is arguably centered around zero offset.

Because we found general agreement between the Lenz et al. (1998) predicted colors and the colors measured with the SDSS PT, we did not to apply a filter correction to the observed data.

3. Observations

In order to test the Lenz et al. (1998) l-parameter vs. metallicity relationship, we needed ugriz observations of stars with known metallicities. Since SDSS photometry is easier to obtain than high resolution spectroscopy, we chose to observe bright stars, selected primarily from the Cayrel deStrobel Catalogue of [Fe/H] (Cayrel de Strobel et al. 1997) with the SDSS PT. The stars were selected within the color range $0.69 < B - V < 0.98$, which approximately corresponds to $0.5 < g - r < 0.8$. If a star turned out to be outside of our color window once the actual SDSS colors were obtained, then it was discarded. Stars were selected to span the range of surface gravities and metallicities in order to test our method over the entire range of l-values. Metallicity values came from the Cayrel deStrobel Catalogue of [Fe/H] determinations. Many of the surface gravities were taken from an updated catalog, Cayrel de Strobel, Soubiran & Ralite (2001). If more than one entry was listed in the catalog, then the entries were averaged.

The measurements of these stars are listed in Table 1, along with the adopted metallicity and the derived value of the l-parameter.

We chose not to correct individual stars selected from the Cayrel de Strobel catalog for reddening, though we have indicated the maximum reddening correction in Fig. 2, since the vast majority of the stars have large galactic latitudes and small distances, suggesting the impact of extinction will be small. To test this, we calculated distances using surface gravity and spectral type where that information was available. We used dust maps (Schlegel, Finkbeiner, & Davis 1998) to determine E(B-V) values in the direction of each star assuming all dust along that line-of-sight lies in front of the star. We calculated the maximum change in u using $A_u = R_u E(B - V)$, and similarly for gri and z, with $R_u = 5.155$, $R_g = 3.793$, $R_r = 2.751$, $R_i = 2.086$, and $R_z = 1.479$ (Stoughton et al. 2002). From this we determined the maximum shift in l for each individual star. We found the average shift to be 0.056 magnitudes toward smaller values of l. Although this correction shifted the observational points toward the theoretical points, the magnitude of each shift is an upper limit and we expect the true shifts to be much smaller.

4. Results

4.1. The l-parameter as an indicator of metallicity for G/K stars

Figure 2 shows metallicity versus the l-parameter for Lenz et al. synthetic stars as well as our observed stars. Black symbols show Lenz et al. (1998) simulated colors of Kurucz model atmospheres. Blue symbols are simulated $ugriz$ colors of Gunn-Stryker stars as presented in Lenz et al. (1998). The magenta points are stars we observed with the PT, with metallicities from the literature. The blue error bars show one sigma errors in the l-parameter, and when more than two metallicity measurements were listed from the literature a one sigma error bar in metallicity is also shown. The magenta lines extending to the left show the effect on the l-parameter of applying the full Schlegel, Finkbeiner, & Davis (1998) reddening correction, assuming all of the extinction in that Galactic direction was in the foreground of the star. For the three stars with very large maximum reddening correction (they are bright stars at low Galactic latitude), the majority of the extinction is surely behind the star. The higher latitude stars with smaller maximum extinction are likely to have most of the extinction in the foreground.

The points show rough agreement with the predictions of Kurucz model atmospheres, with a few outliers. It turns out that stars with measured metallicities from high resolution spectroscopy are not a random set; they are most often unusual stars to begin with. The one star with a much lower metallicity than predicted by photometry are now known to be carbon-enhanced (Beers, private communication). The two stars that are the most discrepant in the other direction (higher metallicity than predicted) were X-ray selected stars. The metallicity of the one star than is a known white dwarf, G 158-100, the metallicity is actually well measured with the l-parameter. Where surface gravities are known, the high surface gravity dwarf stars lie to the right of the lower surface gravity giant stars, as predicted by the Kurucz models.

We extracted SDSS photometry for stars with stellar parameters measured from high resolution spectroscopy in the Hamburg/ESO R-process Enhanced Star Survey (HERES) (Barklem et al. 2005). This netted 10 stars in the color range $0.5 < g - r < 0.8$, with photometry and metallicities listed in Table 2. The locations of these stars in the metallcity vs. l-parameter plot are shown in green in Fig. 2. The photometry for these stars was reddening-corrected, as the stars were faint enough (and therefore far enough away) that we expect most of the extinction to be in the forground of the stars. One of the stars from this data set that falls at lower metallicity than predicted is also now known to be a carbon star. We expect that some of the other stars that are at lower metallicity than predicted could be carbon-enhanced as well.

We also matched stars from the HK catalog, with identified metallicities from medium resolution spectroscopy (Beers 2005), with SDSS photometry from DR4. This netted 13 stars in the $0.5 < g - r < 0.8$ color range; these stars are also shown in green in Fig. 2, with photometry and metallicities listed in Table 2. The photometry for these stars was also reddening-corrected using standard SDSS procedures.

We also had access to *ugriz* data for several open clusters[6] (Rider et al. 2004) with well-determined metallicity. We chose clusters based upon the abundance of data points within our color range of $0.5 < g - r < 0.8$. We found two clusters which fit our constraints: NGC 6134 and NGC 6281. However, the main sequence of NGC 6281 had a width of approximately 0.3 magnitudes within our color range. Since this width could not be explained by photometric error, we concluded that it was heavily contaminated with field stars and therefore it was excluded. We corrected NGC 6134 for reddening assuming E(B-V) = 0.38 magnitudes, and included the cluster as the orange points in Figure 2. Cluster members were identified by their position on the sky, making it possible that field stars were included. At least one of the two outlying members of NGC 6134 in figure 1 could be a field star misidentified as cluster members (the other is possibly a carbon star, as described below). Table 2 lists the dereddened colors, metallicity and l-parameter for stars in NGC 6134 with $0.5 < g - r < 0.8$.

Figure 7 of the Lenz et al. (1998) paper showed cross sections through the stellar locus in three-dimensional color space $(u - g, g - r, r - i)$. The k-parameter was measured along the stellar locus, from the blue end to the red end. Perpendicular to the k-parameter at each location along the locus, two color indices were defined: the l-parameter was along the major axis of the cross section, and the m-parameter was along the narrow axis of the cross section. For normal stars, there is almost no width to the stellar locus at all in the direction of the m-parameter.

To verify that real photometry shows the same properties of the stellar locus in the region $0.5 < g - r < 0.8$, we plot the m-parameter vs. the l-parameter in Figure 3. The dispersion in the direction of the m-axis is not much larger than the photometric errors. Figure 3 should be compared with the d and e panels of Figure 7 from Lenz et al. (1998). Our measured photometry appears to be slightly shifted towards higher values of the m-

[6]http://home.fnal.gov/ crider/openClusters/paper1.html

parameter, but is otherwise the stars are located just as we expect them to be from the predictions of the Kurucz models, with three exceptions that lie well above the stellar locus. BD +09:2384, at $l = -0.151$, is a known carbon star. We have examined the locations of other known carbon stars in color space, and found that they can lie above the locus, below the locus, or they could have colors that show no indication of irregularity. Given that the cluster star NGC6134-10160 is unusual both in the l-parameter and in the m-parameter, it is suggested that this star could also be a carbon star. The alternate possibility, that it is not in fact a member of the NGC 6134 open cluster, would not explain the unusual value of the m-parameter. The star HE0240-0807 is likely to be unusual in some way as well - possibly also a carbon star. The metallicity for this star is a good match to that predicted by the l-parameter.

In Figure 4 we test whether the l-parameter has any sensitivity to surface gravity. We show all of the stars in Table 1 and 2 for which surface gravities have been measured (NGC 6134 cluster stars were arbitrarily assigned a gravity of $\log g = 3.5$, since they are known to be on the giant branch). No correlation is evident in the figure, as expected.

4.2. The v-parameter as an indicator of $\log g$ for A stars

Lenz et al. (1998) also defined a v-parameters that was an indicator of surface gravity for blue stars with color $-0.20 < g - r < 0.25$. We observed two stars in this color range, from the Cayrel de Strobel et al. (1997) catalog, with the SDSS PT; but most of the data we have with both SDSS photometry and measured surface gravities comes from the HK catalog matched to DR4. The stars and their measured parameters are listed in Table 3. Figure 5 reproduces Figure 9 from Lenz et al. (1998) along with the data from the 15 stars in Table 3.

Figure 5 shows that the v-parameter is a useful discriminant for surface gravity of blue stars. The surface gravities are slightly higher than predicted by the Lenz et al. (1998) models, but with roughly the same slope. Surprisingly, the five stars in the smaller color range, $-0.15 < g - r < 0.00$, have a larger dispersion around the best-fit slope than the broader color range, $-0.20 < g - r < 0.25$. This is a contradiction to the expectations from the Kurucz models. The v-parameter appears to be useful over the entire color range selected, but the tigher correlation is for the eight stars with $0.00 < g - r < 0.25$. These stars are all have a measured $\log g$ within 0.4 of the best fit line through the datapoints. The larger data set has about twice the dispersion in $\log g$.

4.3. Evaluation of the s-parameter

Helmi et al. (2003) describes a method for selecting low surface gravity stars in SDSS filters. They select stars with $r < 19$, $-0.1 < P_1 < 0.6$ where $P_1 = 0.91(u-g) + 0.415(g-r) - 1.28$, $1.1 \leq u-g \leq 2.0$, and $0.3 \leq g-r \leq 0.8$. We selected all of the stars in Table 1 and Table 2 that had surface gravity measurements and met the selection criteria. Only one of the stars in Table 2 has a measured surface gravity, and all of the stars in NGC 6134 were excluded by the cut in P_1, which measures the distance along the locus. These stars are shown in Figure 6. There does not appear to be any separation of the stars by gravity with this color index.

Since we have already shown that the stars in this region of color space are well separated by gravity, it is tempting to assume that the s-parameter instead is an indicator of metallicity. Since selecting low metallicity stars would increase the likelihood that the star is a giant in the halo of the Milky Way, this would be consistent with the results of Helmi et al. (2003). Therefore, we used the same selection criteria to select stars from Table 1 and Table 2; this time we select many more of the stars since they all have measured metallicities. The metallicity vs. s'-parameter is shown in Figure 7. Surprisingly, there is very little correlation between the s'-parameter and metallicity, either. The s'-parameter does seem to separate the stars measured with the 2.5 meter telescope (DR4) from the stars measured with the SDSS PT. This is because the 2.5 meter stars have a typical magnitude of $g = 15$, and the SDSS PT stars have a typical magnitude of $g = 10$. The s'-parameter can be re-written as: $s' = -0.239(u-g) + 0.56(g-r) - 0.01g + 0.210$. For stars with the same colors, a difference of 5 magnitudes introduces a shift of 0.05 in the s'-parameter, as we see in Figure 7.

5. Discussion

Our results show rough agreement with the predicted relationship between metallicity ([Fe/H]) and the photometric index l put forth in Lenz et al. (1998), at least for normal stars. Several circumstances make it difficult to determine the accuracy with which metallicity is determined photometrically, including: (1) A large fraction of the best-studied stars were selected because they were unusual in some way; (2) The metallicity measurements of even the best-studied stars are often quite poorly known, or have conflicting measurements; (3) The reddening correction is difficult to determine, especially for the brighter stars that are more likely to have well-studied spectra; and (4) Metallicity measurements are often determined from the same stellar atmospheres models that we are using to predict the metallicity l-parameter relationships.

This last consideration deserved further explanation. The stars listed in the various Cayrel de Strobel catalogs (magenta in Figure 2) have metallicity measurements taken from very many observers with many different techniques and underlying models. The metallicities of the stars in green in Figure 2 have had metallicities measured by a restricted set of researchers, and show better agreement with the Lenz model predictions, especially at intermediate metallicity. The caution here is that these metallicities were determined by comparing colors and line strengths with a very similar set of Kurucz model atmospheres as those used by Lenz et al. to develop the photometric indices, albeit recalibrated against a set of ¿500 metallicity standards (Beers et al. 1999). While it is true that the spectroscopic metallicity determinations use line information unavailable from broadband photometry, there is some danger that our test of the veracity of our photometric indicator is somewhat circular. This caution also applies to a smaller extent to the the test of the v-parameter, since the surface gravities for these stars were determined by comparison with Kurucz models as well.

6. Conclusions

The l-parameter is useful for photometrically separating G/K-stars by metallicity, with the caveat that they can give very incorrect metallicities for unusual stars such as carbon stars and X-ray sources. This technique will be used to select low-metallicity G/K-stars (which we expect to be heavily weighted towards K-giants) in the Sloan Extension for Galactic Underpinnings and Evolution (SEGUE) portion of SDSS II, which officially begins in June 2005.

The v-parameter is useful for photometrically separating A-stars by surface gravity.

The s-parameter photometrically separates G/K stars by magnitude, but is not well correllated with surface gravity or metallicity.

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Fig. 1.— Filter Accuracy Check. This figure shows the difference in synthesized and measured colors as a function of measured color. Black squares represent $i-z$, green xs represent $r-i$, blue circles represent $g-r$, and red asterixes represent $u-g$. Large symbols correspond to Gunn-Stryker stars that were observed with the SDSS PT. Smaller symbols represent stars with measurements of $T_{\rm eff}$, $\log g$, and [Fe/H] from the literature and photometric measurements with the SDSS PT. For the latter stars, synthetic colors were assigned by interpolating the grid of Kurucz models convolved with SDSS filters from Lenz et al. (1998).

Fig. 2.— Metallicity vs. l-parameter. The blue diamonds are Gunn-Stryker stars with colors simulated in Lenz et al. The wheel-like circles are members of NGC 6134. All other points are metallicity standards. Small, solid circles represent stars with high surface gravity ($log(g) > 3.5$) metallicity standards with two concentric circles represent those with low surface gravity ($log(g) < 3.5$) and small circles enclosed by triangles represent stars with unknown surface gravity. Photometry of magenta points was obtained with the PT, while green points were supplied by Beers (2005). Error in the l-parameter is photometric error arising from the observations. Error in metallicity is given by the standard-deviation of multiple metallicity measurements, when available. All other points are simulated colors as given in Lenz et al. The blue lines represent the metallicity categories as discussed in section 5.

Fig. 3.— m-vector versus l-parameter for metallicity standards. Symbols are as described in Figure 2.

Fig. 4.— Surface gravity versus l-parameter for metallicity standards. Orange, wheel-like circles are members of NGC6134, with unknown surface gravities. NGC 6134 is composed of giant stars, allowing us to assume that log(g) = 2.5 in order to include the cluster on this plot. All symbols are as described in Figure 2. We assumed $log(g) = 2.5$ for NGC 6134 members in order to include them on this plot.

Fig. 5.— Surface gravity versus v-parameter. Circular points are theoretical stars simulated in Lenz et al. Solid triangles are observed stars with $-0.15 < g-r < 0.00$. Outlined triangles are observed stars with $-0.20 < g-r < 0.25$.

Fig. 6.— Surface gravity versus s'-parameter. Solid triangles are observed stars with $-0.15 < g-r < 0.00$. Outlined triangles are obsered stars with $-0.20 < g-r < 0.25$.

Fig. 7.— Metallicity versus s'-parameter. The orange, wheel-like circles are members of NGC 6134. All other points are metallicity standards. Small, solid circles represent stars with high surface gravity, two concentric circles represent low surface gravity, and small circles enclosed by triangles represent unknown surface gravity, as described in Figure 2.

Error in the s'-parameter arises from photometric error, and the error in the metallicity is given as the standard-deviation of multiple metallicity measurements, when available.

Table 1. Metallicity Standards with $0.5 < g - r < 0.8$

Star Name	g	error	u-g	error	g-r	error	r-i	error	i-z	error	l	error	[Fe/H]	log g	re
LP685-47	12.910	0.004	1.310	0.014	0.640	0.005	0.310	0.004	0.190	0.006	0.249	0.004	-2.79	2.50	
Ross 740	13.070	0.012	1.150	0.128	0.570	0.014	0.280	0.015	0.140	0.018	0.253	0.051	-2.75	3.20	
BD -01:1792	11.640	0.008	1.700	0.011	0.650	0.009	0.270	0.006	0.140	0.009	0.063	0.003	-0.80	3.00	
BPS CS 22952-015	13.650	0.014	1.459	0.026	0.652	0.023	0.287	0.026	0.175	0.036	0.179	0.004	-3.38	1.3	
BPS CS 22949-037	14.733	0.011	1.414	0.032	0.632	0.027	0.287	0.033	0.150	0.024	0.185	0.013	-3.58	2.08	
HD 107752	10.371	0.002	1.477	0.005	0.649	0.004	0.303	0.004	0.144	0.002	0.178	0.002	-2.74	1.25	
HD 126587	9.505	0.001	1.441	0.004	0.673	0.001	0.300	0.001	0.178	0.001	0.209	0.001	-2.69	2.02	
HD 149414	9.943	0.001	1.363	0.003	0.562	0.001	0.227	0.001	0.117	0.002	0.124	0.001	-1.31	4.35	
BPS CS 22878-101	14.130	0.014	1.532	0.024	0.691	0.021	0.329	0.025	0.187	0.035	0.198	0.004	-3.13	1.15	
BD +09:2384	10.311	0.005	2.143	0.007	0.647	0.006	0.239	0.004	0.133	0.003	-0.151	0.001	-0.71	3.0	
BPS CS 22949-048	14.049	0.008	1.359	0.017	0.647	0.010	0.314	0.008	0.178	0.010	0.235	0.003	-3.17	1.10	
BD +10:2495	10.051	0.002	1.326	0.003	0.573	0.003	0.238	0.003	0.120	0.005	0.154	0.001	-1.83	–	
BD +12:2547	10.349	0.002	1.734	0.005	0.728	0.003	0.301	0.003	0.162	0.004	0.120	0.001	-0.72	–	
G 158-100	15.201	0.002	1.101	0.007	0.510	0.007	0.222	0.003	0.092	0.002	0.200	0.002	-2.64	–	
Wolf 365	11.695	0.002	1.182	0.007	0.560	0.003	0.237	0.003	0.097	0.002	0.207	0.002	-2.23	4.50	
Ross 838	11.900	0.002	1.277	0.007	0.573	0.003	0.239	0.003	0.111	0.002	0.177	0.002	-1.60	4.00	
GCRV 9483	11.631	0.002	1.106	0.007	0.527	0.003	0.222	0.003	0.082	0.002	0.209	0.002	-2.01	4.16	
HD 212753	10.071	0.002	1.651	0.003	0.652	0.002	0.198	0.003	0.090	0.004	0.045	0.001	-0.51	4.5	
HD 4906	9.113	0.003	1.468	0.004	0.581	0.003	0.196	0.002	0.083	0.003	0.074	0.001	-0.84	3.57	
SAO 130113	9.968	0.003	1.570	0.005	0.623	0.003	0.267	0.003	0.137	0.005	0.099	0.001	0.00	4.5	
HD 224087	9.312	0.003	1.620	0.005	0.618	0.004	0.230	0.004	0.073	0.006	0.047	0.001	-0.25	4.42	
HD 293857	9.591	0.003	1.448	0.005	0.546	0.005	0.183	0.005	0.075	0.006	0.051	0.001	0.00	4.50	
HD 35179	9.941	0.003	1.879	0.005	0.739	0.004	0.276	0.004	0.159	0.004	0.050	0.001	-0.67	1.60	
HD 20146	8.734	0.003	1.549	0.006	0.505	0.004	0.143	0.004	0.030	0.004	-0.045	0.001	0.00	–	
HD 285773	9.301	0.003	1.758	0.005	0.610	0.003	0.185	0.003	0.071	0.004	-0.039	0.001	0.05	4.47	

[1]Cayrel de Strobel et al. (1997)

[2]Beers et al. (1999)

[3]Reid et al. (2001)

Table 2. Dereddened Metallicity Standards with $0.5 < g - r < 0.8$

Star Number	g	u-g	g-r	r-i	i-z	l	[Fe/H]	ref
NGC6134-248	10.988	1.844	0.574	0.159	0.010	-0.116	0.18	[1]
NGC6134-273	11.176	2.029	0.682	0.191	0.027	-0.104	0.18	[1]
NGC6134-289	11.195	1.954	0.639	0.174	0.035	-0.111	0.18	[1]
NGC6134-313	11.259	2.012	0.641	0.180	0.005	-0.131	0.18	[1]
NGC6134-390	11.467	2.022	0.650	0.167	0.027	-0.137	0.18	[1]
NGC6134-10166	10.279	2.452	0.717	0.266	0.092	-0.221	0.18	[1]
NGC6134-10220	10.701	1.845	0.682	0.194	0.058	-0.022	0.18	[1]
NGC6134-10333	11.157	2.067	0.663	0.187	0.045	-0.136	0.18	[1]
NGC6134-10348	11.193	1.945	0.635	0.179	0.033	-0.106	0.18	[1]
NGC6134-10370	11.251	1.987	0.625	0.165	0.029	-0.140	0.18	[1]
NGC6134-10424	11.365	1.846	0.739	-3.693	3.685	-2.214	0.18	[1]
NGC6134-10427	11.410	1.898	0.620	0.167	0.021	-0.104	0.18	[1]
HE0240-0807	15.409	1.628	0.693	0.413	0.063	0.207	-2.68	[3]
HE0315+0000	15.631	1.257	0.589	0.239	0.125	0.229	-2.73	[3]
HE1132+0204	14.946	1.154	0.511	0.222	0.110	0.177	-2.55	[3]
HE1212-0127	16.221	1.446	0.630	0.272	0.121	0.161	-2.15	[3]
HE1219-0312	16.181	1.096	0.508	0.201	0.083	0.188	-2.81	[3]
HE1254+0009	14.529	1.386	0.593	0.291	0.104	0.172	-2.94	[3]
HE1256-0228	16.261	1.267	0.551	0.243	0.109	0.168	-2.07	[3]
HE1345-0206	15.906	1.166	0.530	0.249	0.134	0.201	-2.82	[3]
HE2143+0030	15.609	1.553	0.674	0.308	0.120	0.165	-2.43	[3]
HE2319-0852	15.503	1.524	0.659	0.276	0.131	0.149	-3.38	[3]
160270010	14.372	1.530	0.546	0.166	0.071	0.005	-0.94	[2]
160290131	13.934	1.785	0.666	0.239	0.126	0.019	-0.65	[2]
160770004	14.336	1.493	0.538	0.126	0.005	-0.007	-0.97	[2]
160820132	15.536	1.643	0.626	0.235	0.103	0.051	-0.48	[2]
164730071	14.073	1.401	0.549	0.216	0.023	0.092	-1.03	[2]
165520117	15.173	1.819	0.722	0.252	0.119	0.051	-1.00	[2]
171410034	14.723	1.672	0.552	0.113	0.000	-0.083	-1.26	[2]
174360058	14.094	1.293	0.502	0.170	0.128	0.080	-2.36	[2]
174360075	14.372	1.472	0.507	0.143	0.090	-0.010	-0.97	[2]
295170031	15.022	1.720	0.577	0.136	0.058	-0.073	-2.70	[2]
303060114	14.206	1.911	0.726	0.231	0.139	0.001	-1.03	[2]
303110077	14.916	1.418	0.505	0.195	-0.012	0.042	-0.46	[2]
303110079	14.978	1.494	0.538	0.146	0.102	0.004	-0.81	[2]

[1]Rider et al. (2004)

[2]Beers (2005)

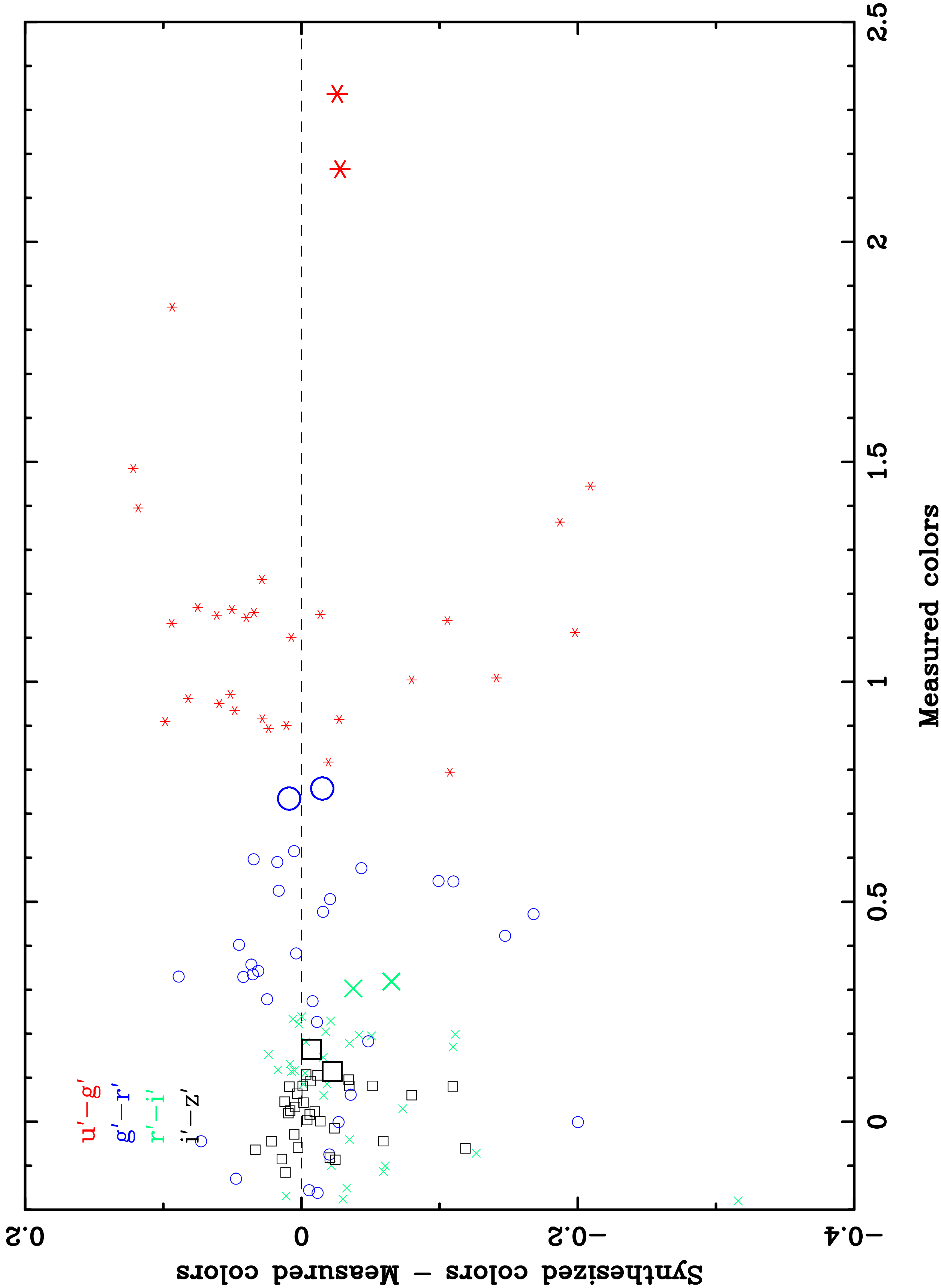
[3]Barklem et al. (2005)

Table 3. A-type Stars with $-0.20 < g - r < 0.25$

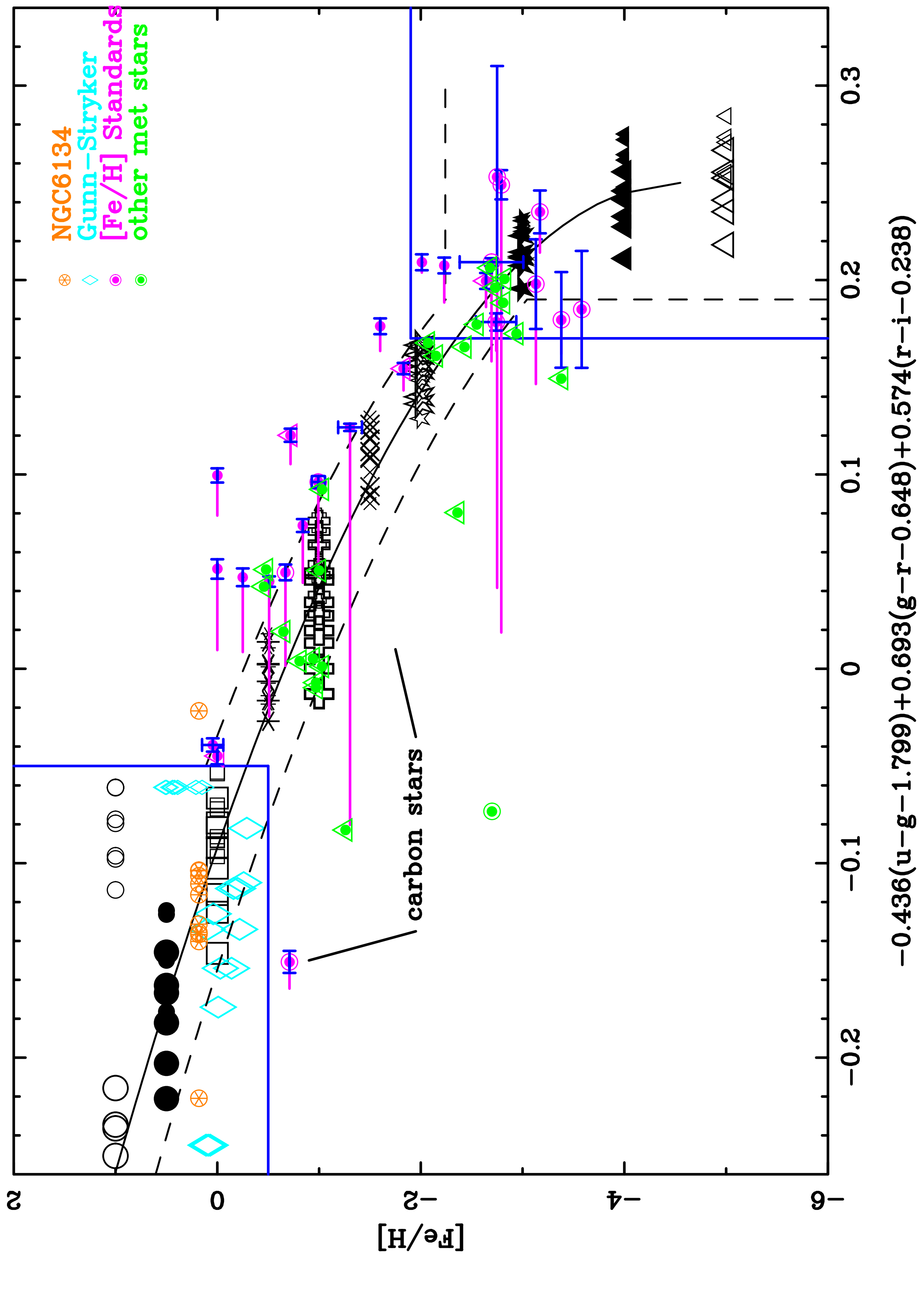
Star	g	u-g	g-r	r-i	i-z	v	log g	ref
BD+25:1981	9.414	0.925	0.144	0.140	-0.037	0.189	4.50	[1]
BD+9:2190	11.287	0.902	0.238	0.076	0.009	0.212	4.11	[1]
160270018	15.083	0.942	0.231	0.103	-0.340	0.206	3.50	[2]
160270051	15.206	1.204	0.057	0.011	-0.019	0.311	2.40	[2]
160270059	13.771	1.094	-0.150	-0.146	-0.127	0.199	3.90	[2]
160270069	14.909	1.084	0.097	-0.006	-0.061	0.223	3.50	[2]
171390007	14.526	0.811	0.241	0.111	0.033	0.220	3.66	[2]
228830013	14.348	1.245	-0.117	-0.078	-0.097	0.284	3.10	[2]
228830050	14.222	1.123	0.026	-0.040	-0.099	0.215	3.60	[2]
228830051	14.873	1.217	-0.047	-0.133	-0.0950	0.228	4.60	[2]
228900038	15.061	1.204	-0.054	-0.054	-0.066	0.285	2.50	[2]
228900068	13.833	1.167	-0.150	-0.180	-0.062	0.254	3.30	[2]
228940014	14.398	1.090	-0.177	-0.118	-0.061	0.271	3.30	[2]
22890034	14.726	1.131	-0.012	-0.080	-0.036	0.260	2.30	[2]
228940036	15.092	1.094	0.199	0.055	0.015	0.276	2.70	[2]

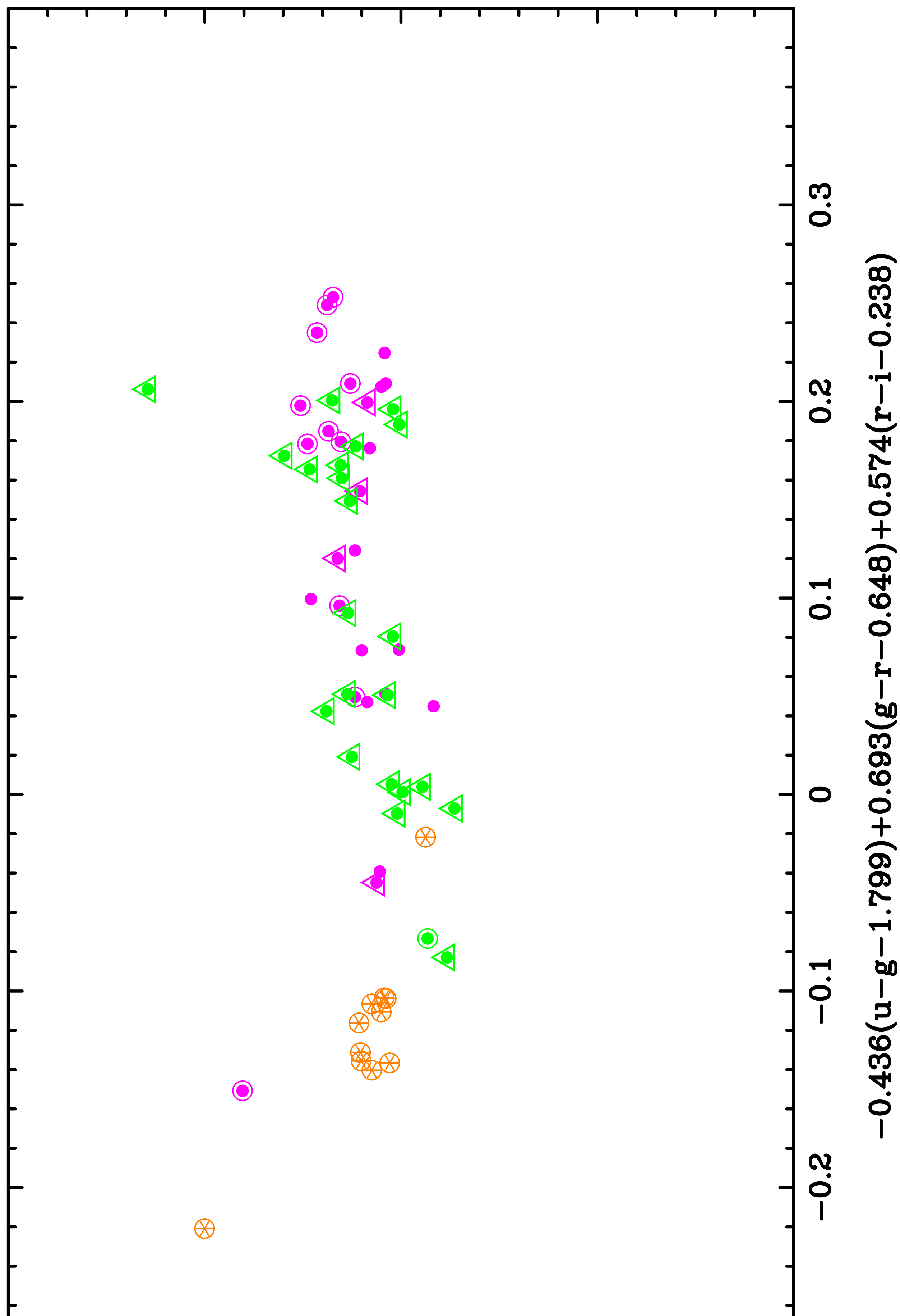
[1]Cayrel de Strobel et al. (1997)

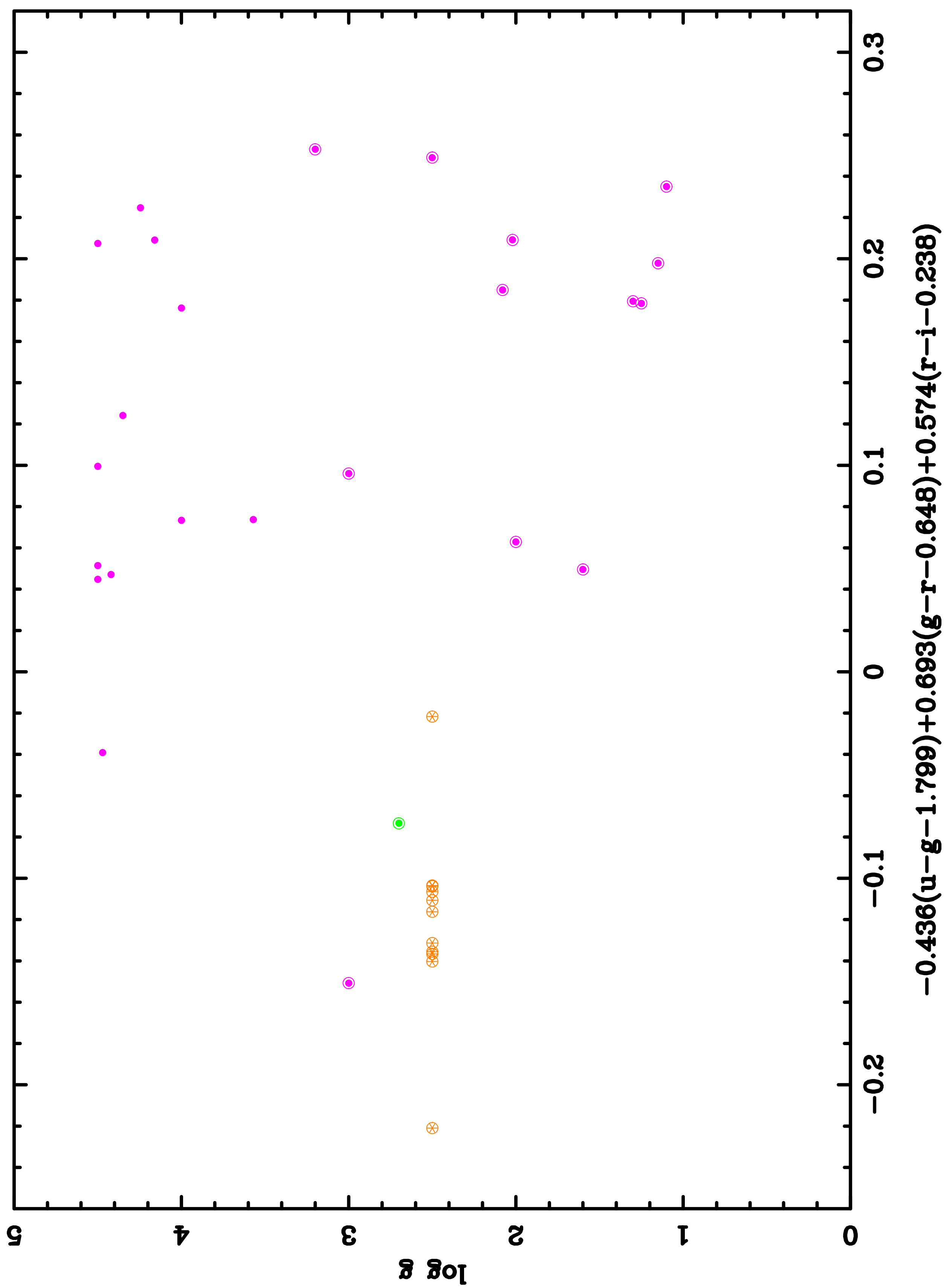
[2]Beers (2005)



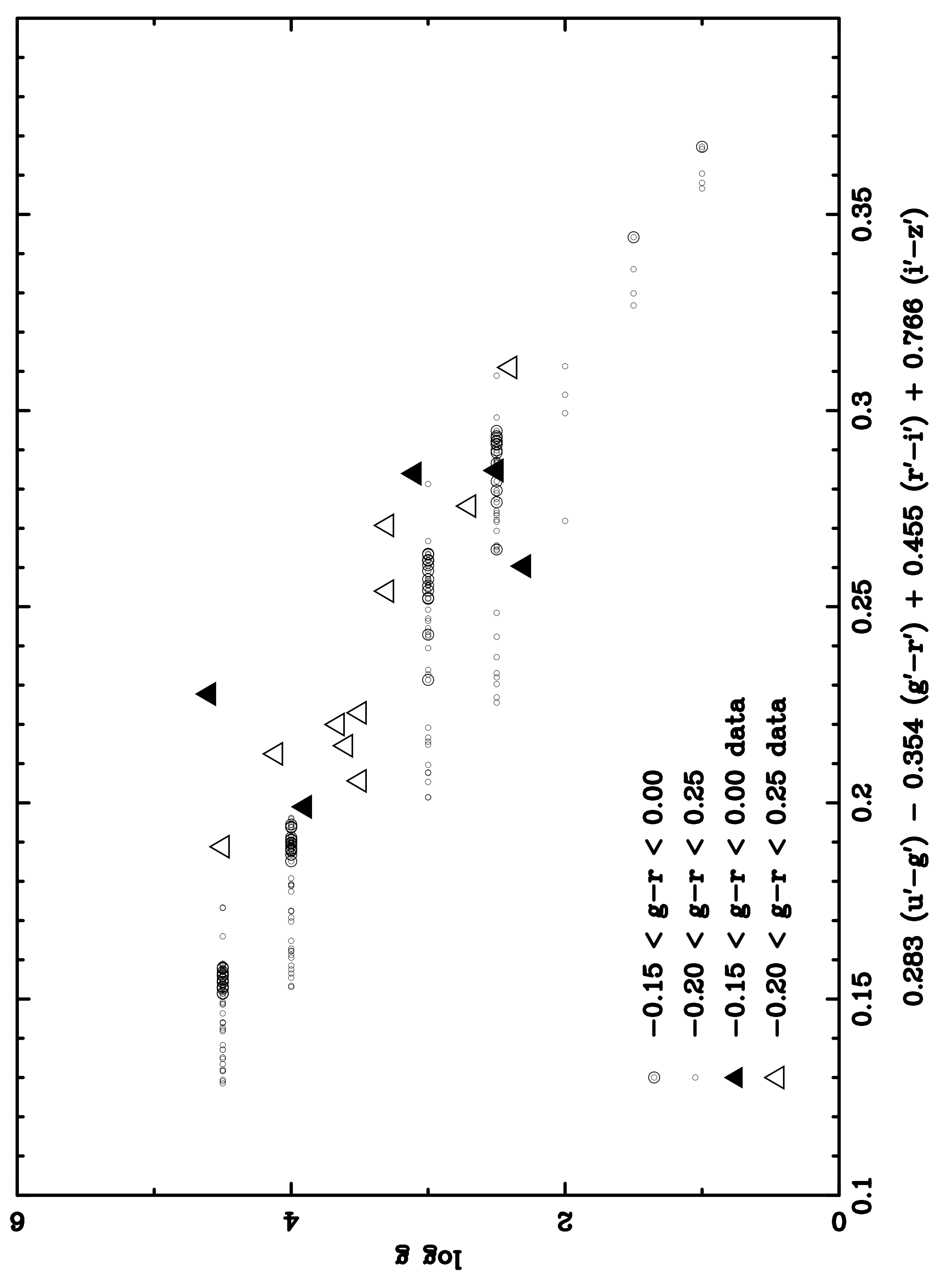
Synthesized colors − Measured colors
Measured colors
u′−g′
g′−r′
r′−i′
i′−z′
0.2
0
−0.2
−0.4
0
0.5
1
1.5
2
2.5


NGC6134
Gunn-Stryker
[Fe/H] Standards
other met stars
carbon stars
[Fe/H]
−0.436(u−g−1.799)+0.693(g−r−0.648)+0.574(r−i−0.238)

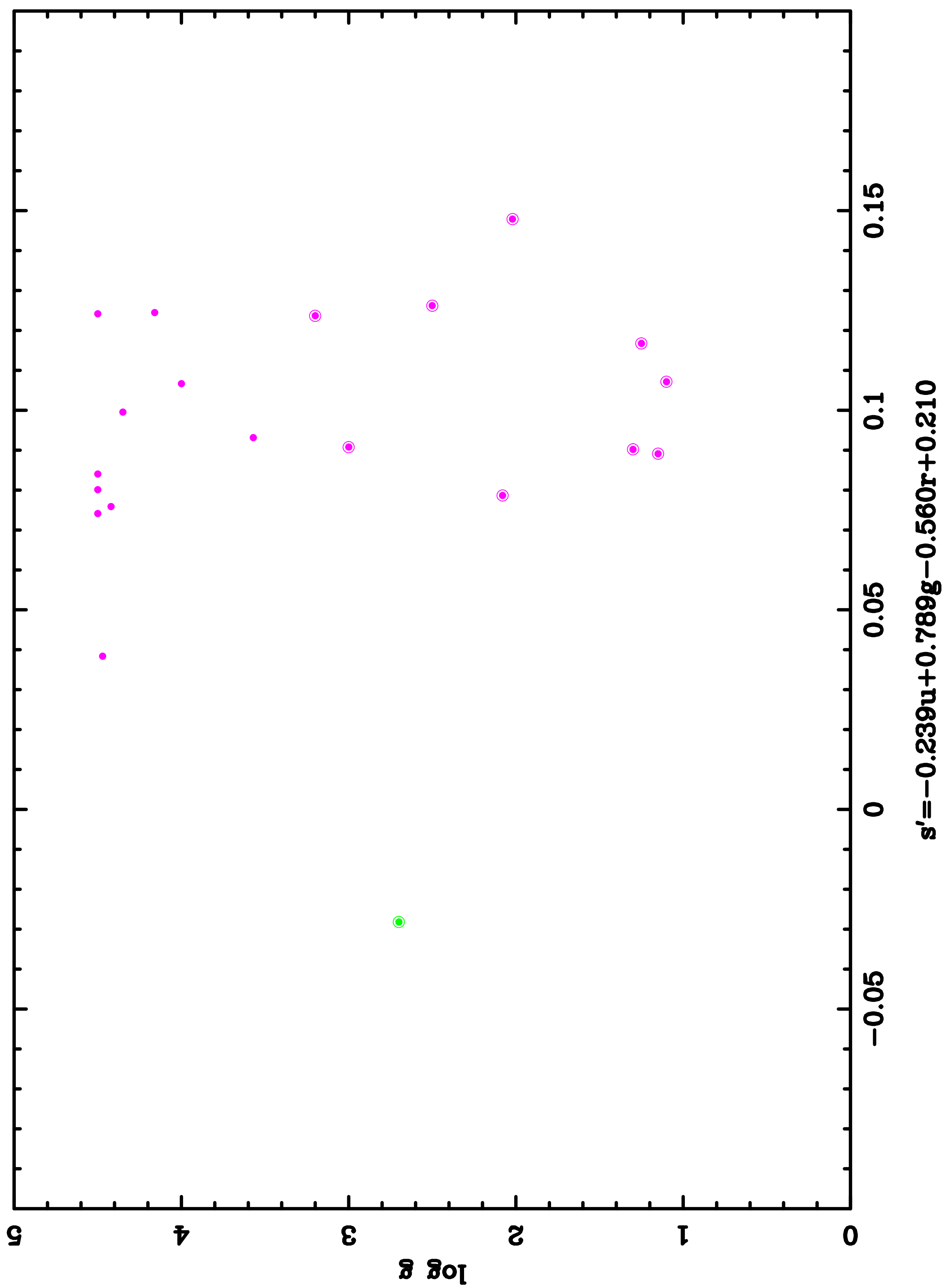

−0.436(u−g−1.799)+0.693(g−r−0.648)+0.574(r−i−0.238)
−0.2
−0.1
0
0.1
0.2
0.3

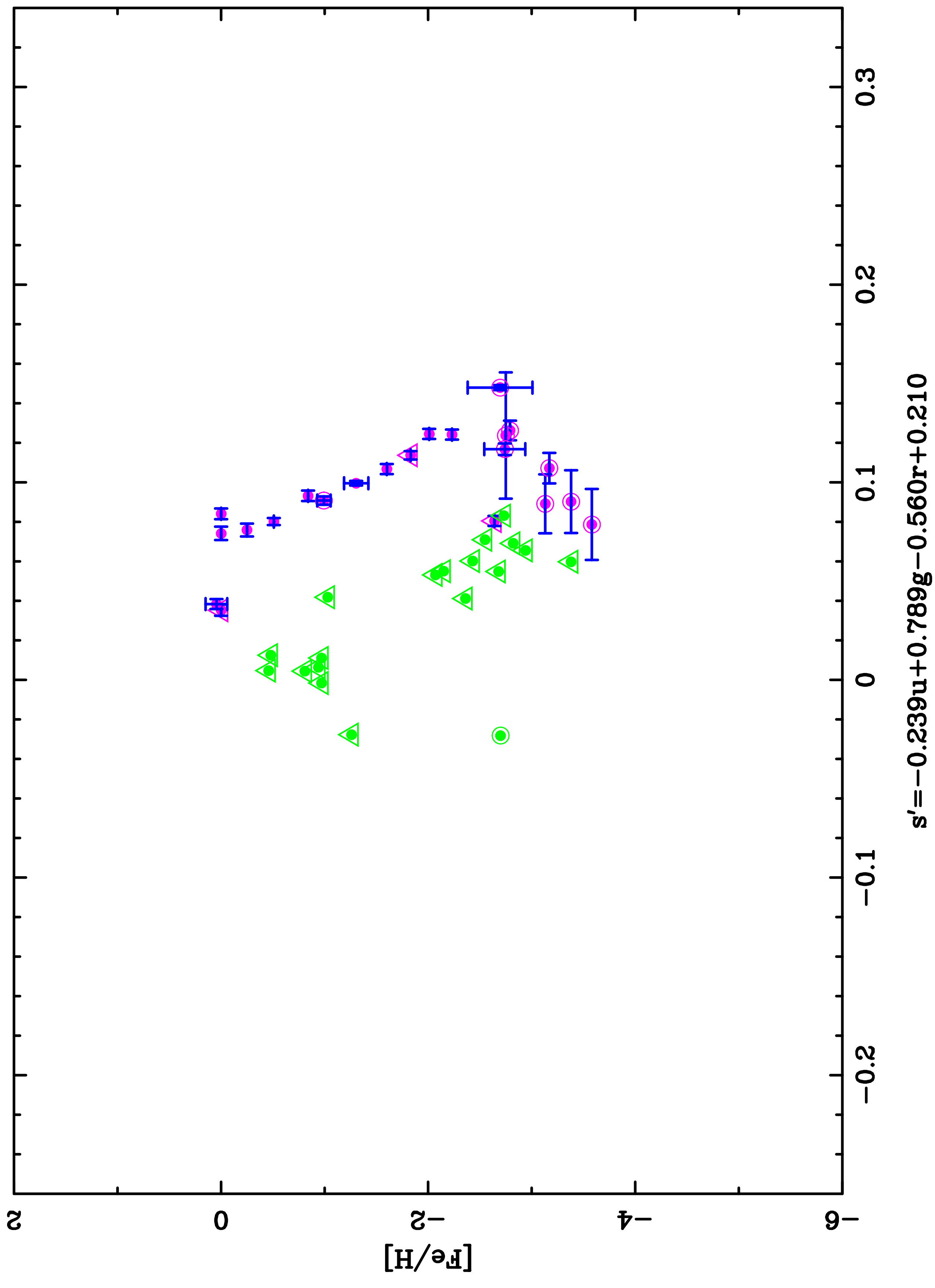


−0.436(u−g−1.799)+0.693(g−r−0.648)+0.574(r−i−0.238)
log g
−0.2
−0.1
0
0.1
0.2
0.3
0
1
2
3
4
5



log g
0.283 (u′−g′) − 0.354 (g′−r′) + 0.455 (r′−i′) + 0.766 (i′−z′)
−0.15 < g−r < 0.00
−0.20 < g−r < 0.25
−0.15 < g−r < 0.00 data
−0.20 < g−r < 0.25 data


log g
s′=−0.239u+0.789g−0.560r+0.210
0
1
2
3
4
5
−0.05
0
0.05
0.1
0.15



[Fe/H]
s'=−0.239u+0.789g−0.560r+0.210