SEATTLE UNIVERSITY

Photometric Metallicities of dSph Stellar Populations

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PROBLEM: There are so few upper RGB stars in the SDSS-discovered dSphs, how can we find them without extensive spectroscopy?

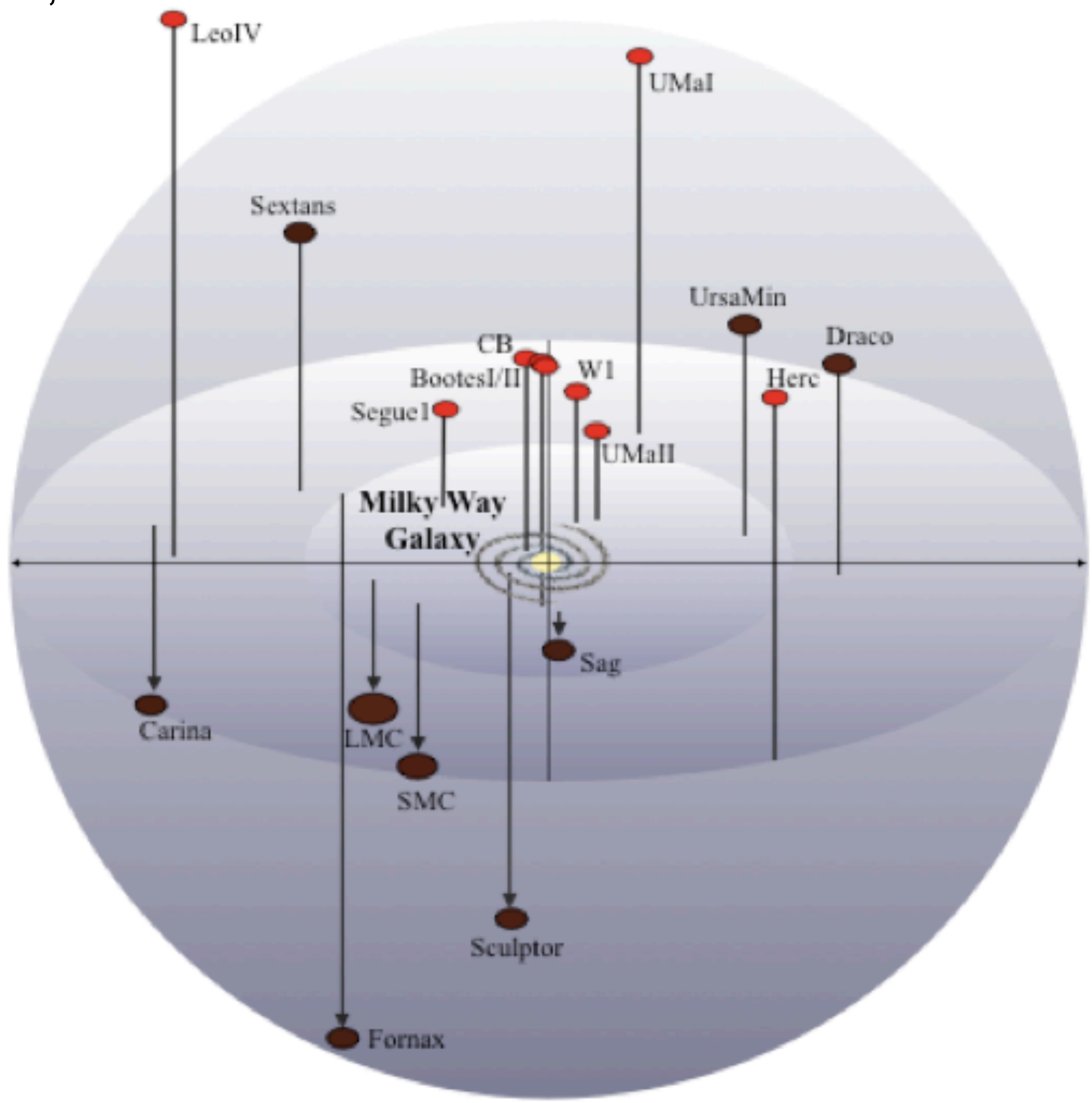
•**Frebel, Simon & Kirby 2011, AAS 21714704:**
"The Chemical Composition Of Ultra-faint Dwarf Galaxies"
Observed extremely metal-poor stars in Uma II, Com Ber, Leo IV,
Segue 1 Bootes II.
[~17 hours per star to get a decent spectrum at Magellan – bad seeing!]
Frebel, A., Kirby, E., & Simon, J. D. 2010b, *Nature in press, astro-ph/0912.4734*

•Recent papers on the best color-pairs to use for age and metallicity studies (e.g., Li & Han 2008, MNRAS, 385, 1270; Holtzman et al. 2011, *AAS 21715310).*
However, much of the work is theoretical
and involves testing on local, highly populated globular clusters.

•**What filter sets are practical for the nearby dSphs?**

300 < $L_\odot$ < 100,000

M/L > 100



[Fe/H] ~ -2.5   Some stars in UMa II, Segue 1, Boo I are below -3.5

Norris et al. 2010 *ApJ* 711 350, Norris et al. ApJ 722 L104, Frebel et al. 2010, IAUS 265 237

SDSS-selected dwarf galaxies to be observed from APO (positions in J2000) & and the WLM dIrr Galaxy.

Field	RA	Dec	D(kpc)	r_h(')	Comments
UMa II	08:51:30	+63:07:48	32	2.0	[Fe/H] spread likely. Muñoz, Geha & Willman (2009) detect signs of tidal interactions.
SEGUE 1	10:07:04	+16:04:55	23	4.5	Star cluster or dSph? Geha et al. (2009) say the latter.
Willman 1	10:49:37	+51:03:04	35	1.75	
Com Ber	12:26:59	+23:54:15	44	5.0	[Fe/H] spread possible. Muñoz, Geha & Willman (2009) do not find signs of tidal interactions.
CVn I	13:28:03.5	+38:33:33.2	210	8.5	
CVn II	12:57:10	+34:19:15	160	3.0	
Boötes II	13:58:00	+12:51:00	50	4.1	
Boötes I	14:00:06	+14:30:00	66	13.1	One paper published, another in preparation, [Fe/H] spread confirmed by other authors (Hughes, Wallerstein & Bossi 2008; Norris et al. 2008; Ivans et al. 2009).
WLM North	00:01:45.53 8	15:25:00.27 0	932 +/- 33	5.5'x2.2'	

Coordinates are J2000.

APO Target list

~70% of data collected.

Hughes, Wallerstein, Leaman, Venn, Cole, plus extras.

Discovery of Ultra-Faint Dwarfs

The Astrophysical Journal, 647: L111–L114, 2006 August 20

A FAINT NEW MILKY WAY SATELLITE IN BOOTES

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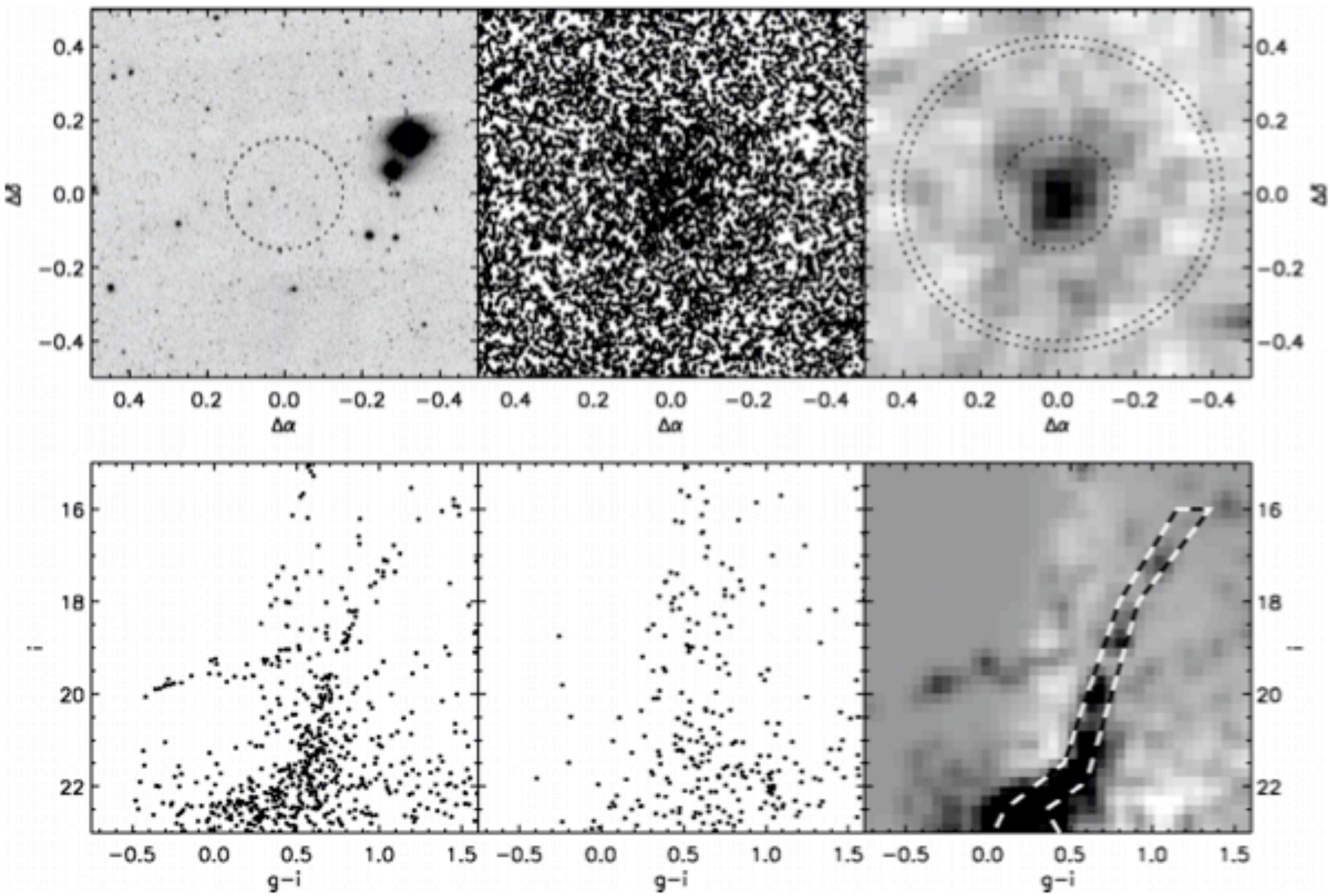
ABSTRACT

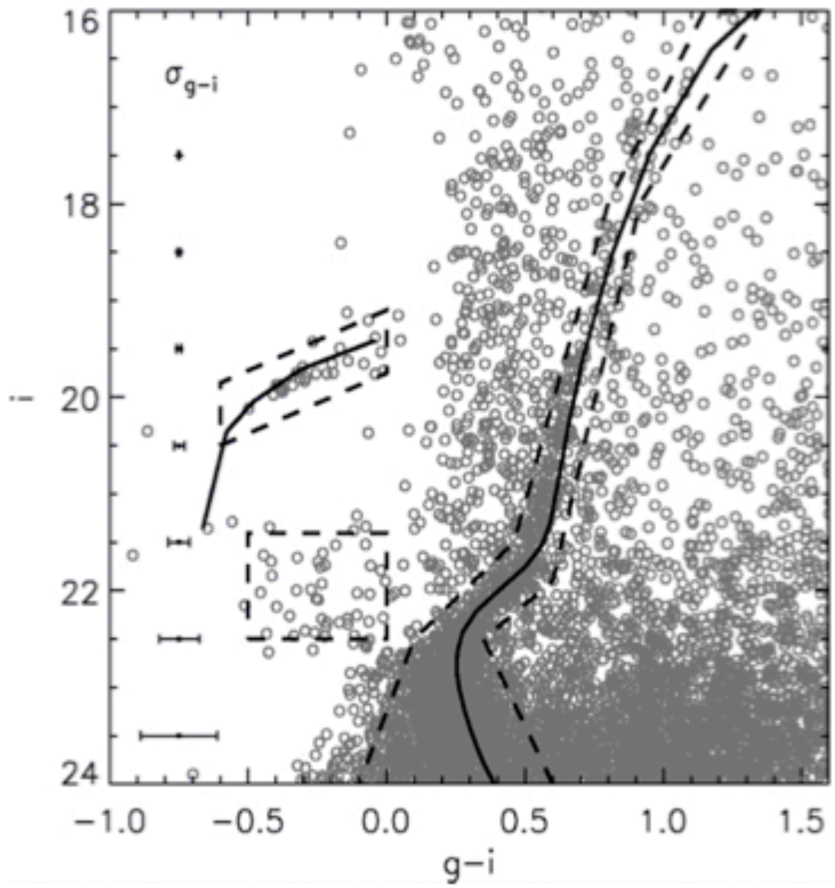
We announce the discovery of a new satellite of the Milky Way in the constellation of Bootes at a distance of ~60 kpc. It was found in a systematic search for stellar overdensities in the north Galactic cap using Sloan Digital Sky Survey Data Release 5. The color-magnitude diagram shows a well-defined turnoff, red giant branch, and extended horizontal branch. Its absolute magnitude is $M_V \sim -5.8$ mag, which makes it one of the faintest galaxies known. The half-light radius is ~220 pc. The isodensity contours are elongated and have an irregular shape, suggesting that Boo may be a disrupted dwarf spheroidal galaxy.

Subject headings: galaxies: dwarf — galaxies: individual (Bootes) — Local Group



Willman (2010, arXiv:0907.4758) wrote a thorough review of the search methods, for these “least luminous galaxies”, which can be as faint as 10^{-7} times the luminosity of the Milky Way.

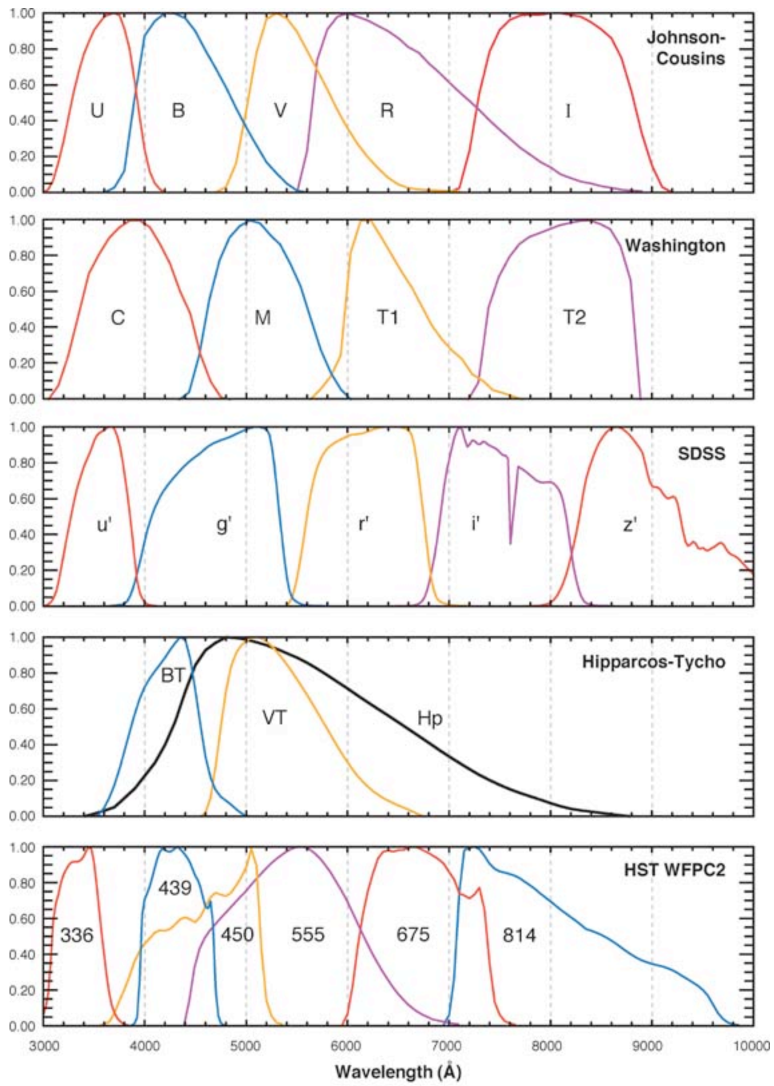
Belokurov et al.



Too many MWG stars and not enough [Fe/H] sensitivity in g

Problem with Sloan filters

—CMD of Boo derived from CTIO data. Overplotted is the ridge line for the old, metal-poor globular cluster M92. The dashed lines are used to select stars belonging to the main sequence, giant branch, and horizontal branch of the satellite. For each magnitude bin, the mean color error is shown on the left-hand side.



Bessell, MS. 2005
Annu. Rev. Astron. Astrophys. 43: 293–336

Strömgren Filters

$m_1=(v-b)-(b-y)$

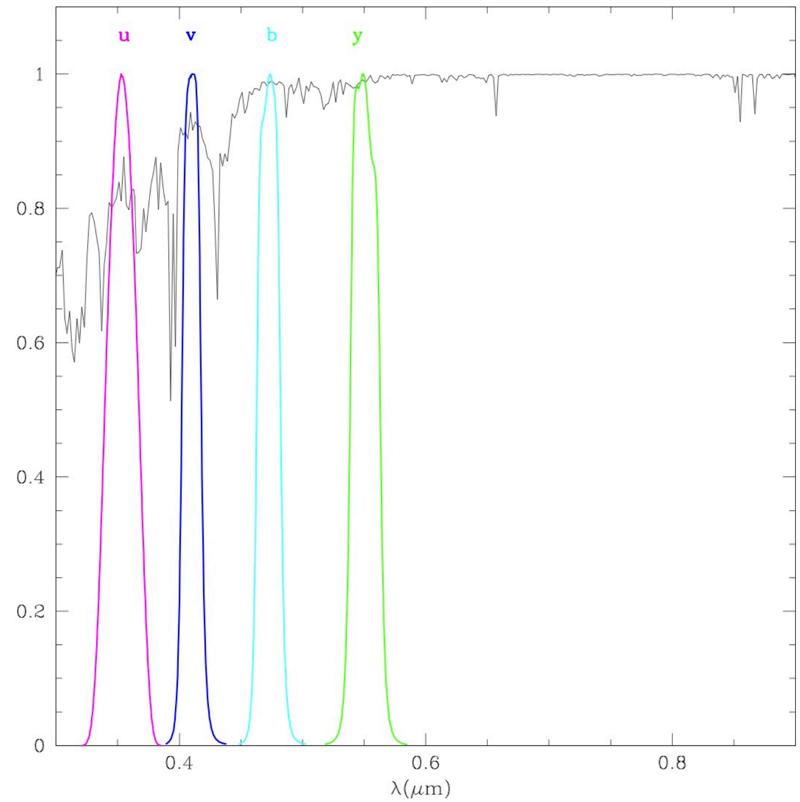
$c_1=(u-v)-(v-b)$

Strömgren B. 1956, Vistas in Astron. 2, 1336

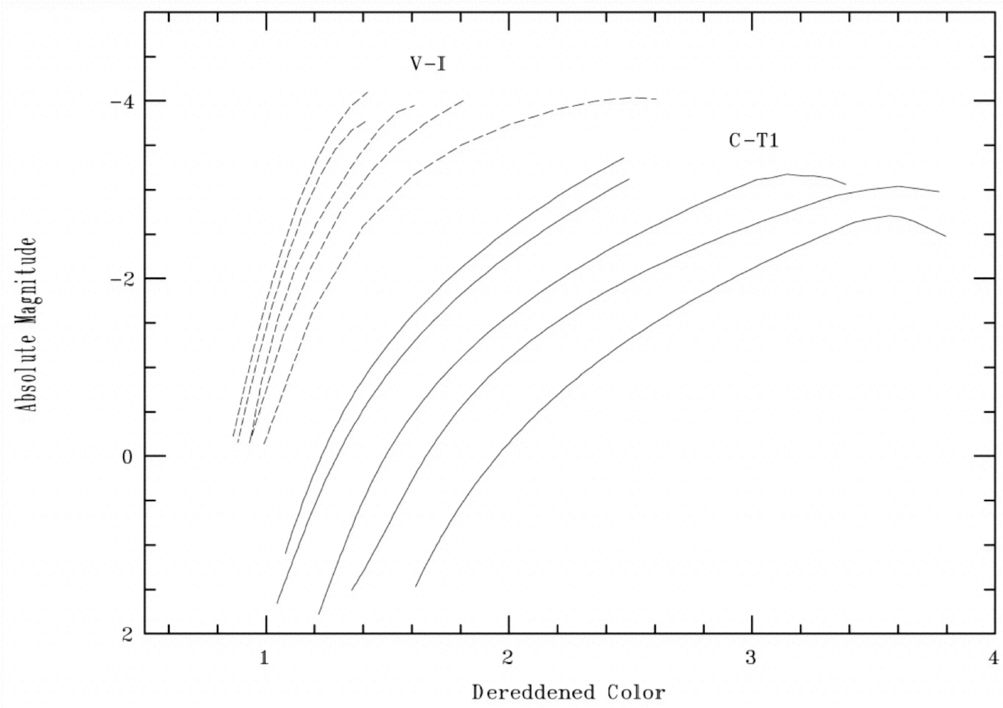
Crawford D.L., Mander J. 1966, Astron. J. 71, 114

The metallicity of the stars is sensitive to the m_1 -index. The color (b-y) is a measure of the temperature and (v-b) is a measure of metallic line blanketing. Recent papers by Feltzing et al. (2008) & Arnadottir, Feltzin & Lundstrom (2010) discuss the properties of the uvby system, and how well the m_1 and c_1 indices can reproduce metallicities anddifferentiate between giant and dwarf stars in the Milky Way.

Filter	Central wavelength [Å]	Width[Å]	Remarks
u	3500	300	
v	4110	190	
b	4670	180	
y	5470	230	
beta narrow	4858	29	(Kitt Peak no 9)
beta wide	4850	129	(Kitt Peak no 10)

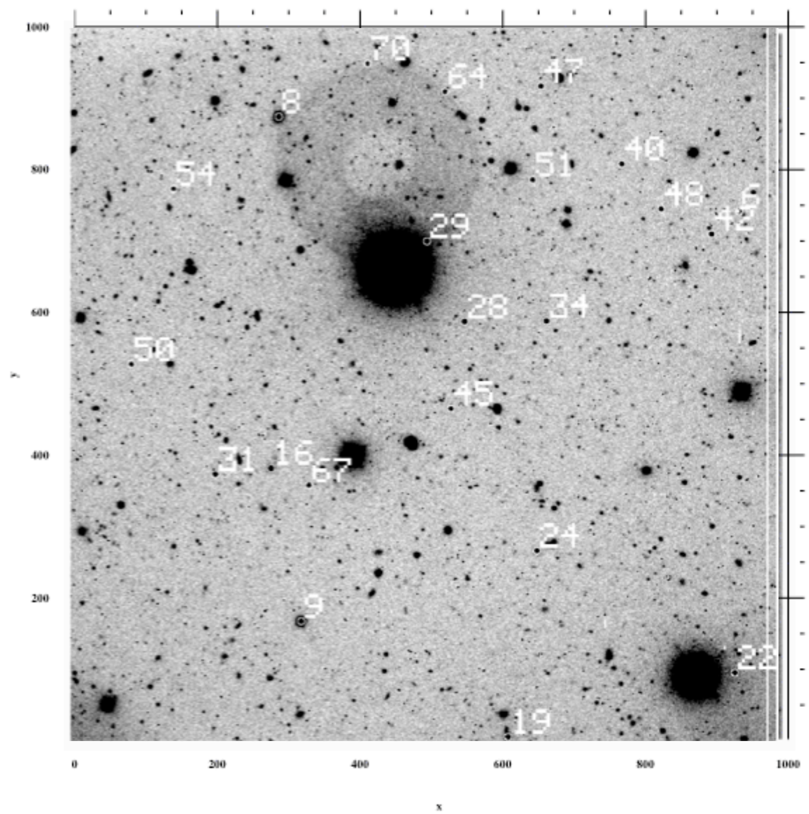


C-T_1 gives better metallicity resolution than (T_1-T_2) vs. (C-T_1)
- Best for -0.5<[Fe/H]<-2.0



The Geisler & Sarajedini (1999; GS99) comparison of the RGBs in V, I and Washington colors. The clusters are (left to right) NGC 7078, NGC 6397, NGC 6752, NGC 1851, and NGC 104. Note that the Washington standard giant branches are much more widely separated than the V, I RGBs.

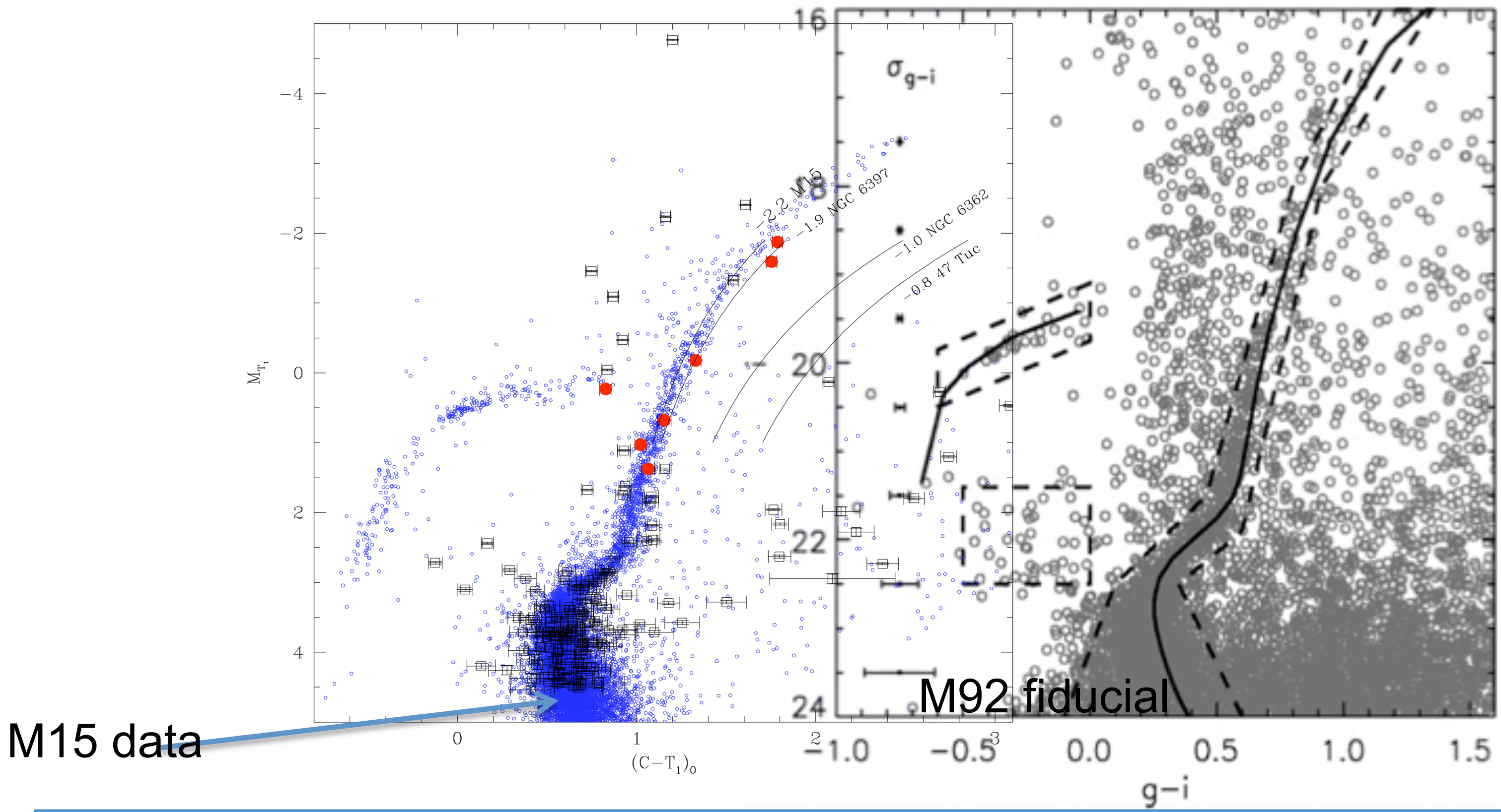
Washington CT_1T_2 (actually CRI)
Strömgren vby



APO SPIcam (4.8'x4.8') 300s R-image, centered on 14h00m30s, 14.5^o

The numbered stars are those statistically identified as members (including 6 redial-velocity IDs) – r_h~ 13'

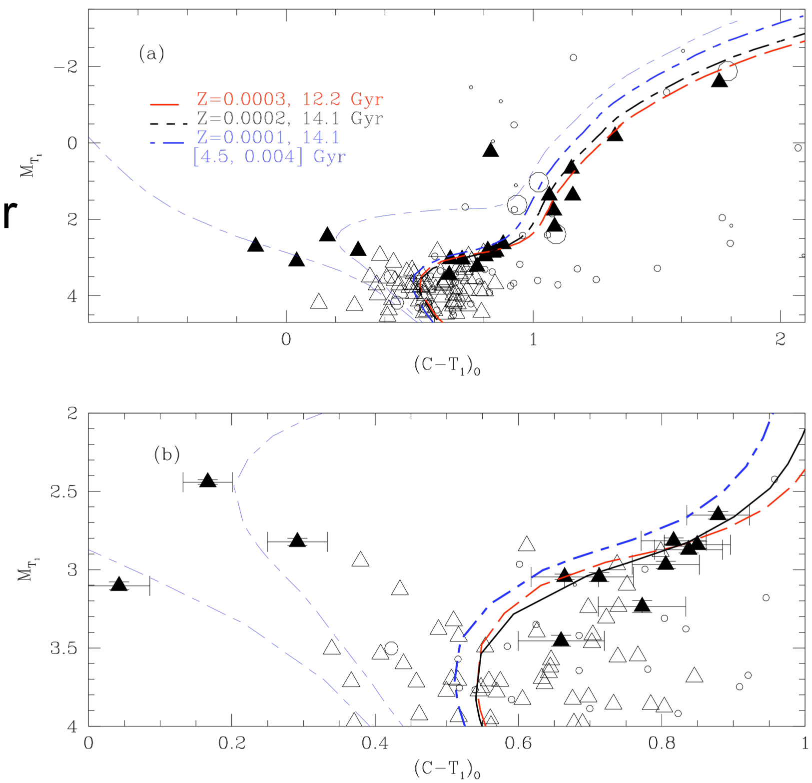
Data from Hughes, Wallerstein & Bossi (2008).



THE WASHINGTON FILTERS ARE MORE EFFICIENT AT SEPARATING THE METAL-POOR DSPH STARS FROM THE GALACTIC FOREGROUND FIELD STARS

CMD for Boo I Stars
Hughes, Wallerstein & Bossi (2008; HWB)

Spread in [Fe/H]?
Spread in age?
Usually: RGB stars for [Fe/H] & MSTO for age.



(a) CMD for Boötes I stars. Filled triangles are class A, open triangles are class B, the classes C-F are decreasing sizes of open circles. For the filled triangles, the error bars are the same size as the points. We show various isochrones from Marigo et al. (2008), including those close to the possible blue stragglers. The classes mean how confident we are of Boo I membership.

(b) MSTO-SGB region of the CMD. Class A objects (filled triangles) have error bars, which are much larger on the other points and are not shown (class B, open triangles, are shown for their general trend). We show the isochrones from Marigo et al. (2008).

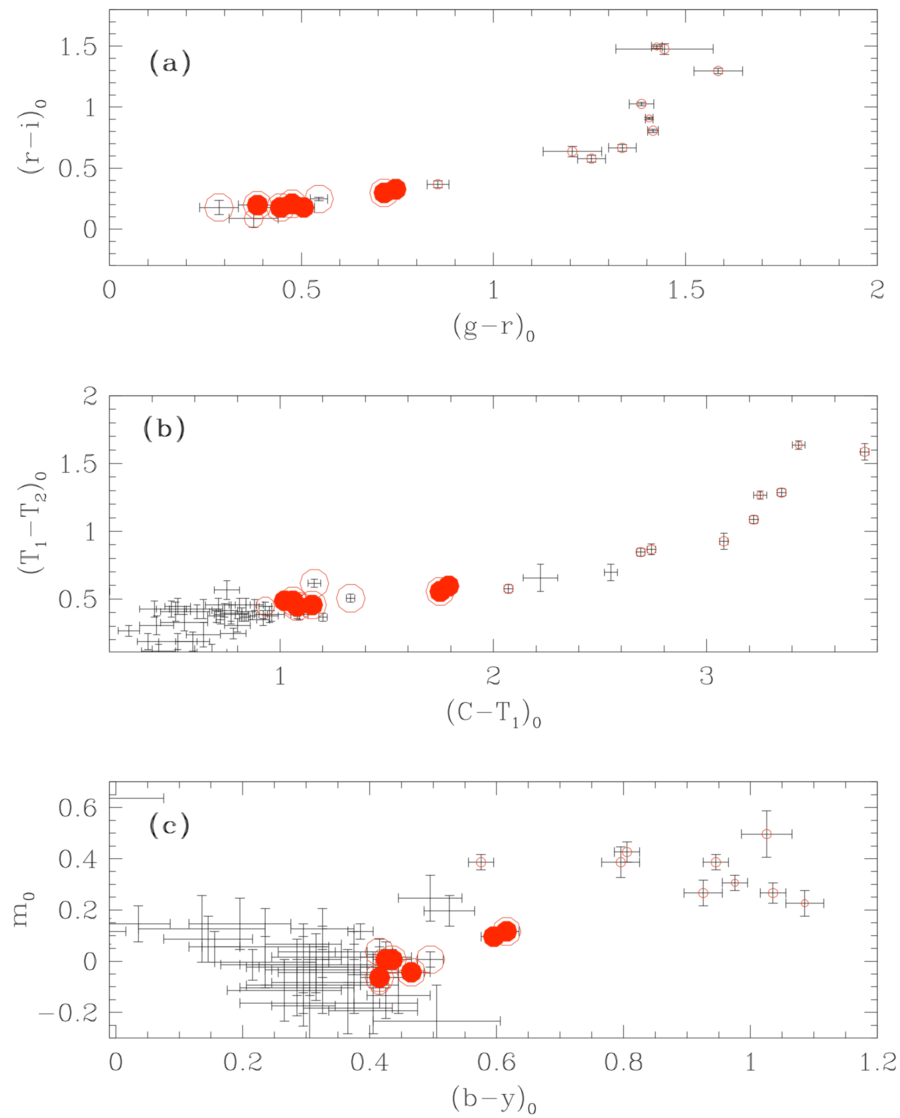
Which filter set works best for this population?

(a) Sloan filter color-color plot for 19 objects having **ugriz** magnitudes. The **u**-band detections have low S/N and are not used.

(b) Washington colors.

(c) Strömgren colors – stars are too faint for u-band - getting sufficient signal-to-noise in the u- and v-bands is challenging at 66 kpc.

The radial-velocity confirmed members are shown as the red filled-circles (Martin et al. 2007).



The SDSS photometry is not sensitive enough to this difference in colors to distinguish this level of metallicity spread.

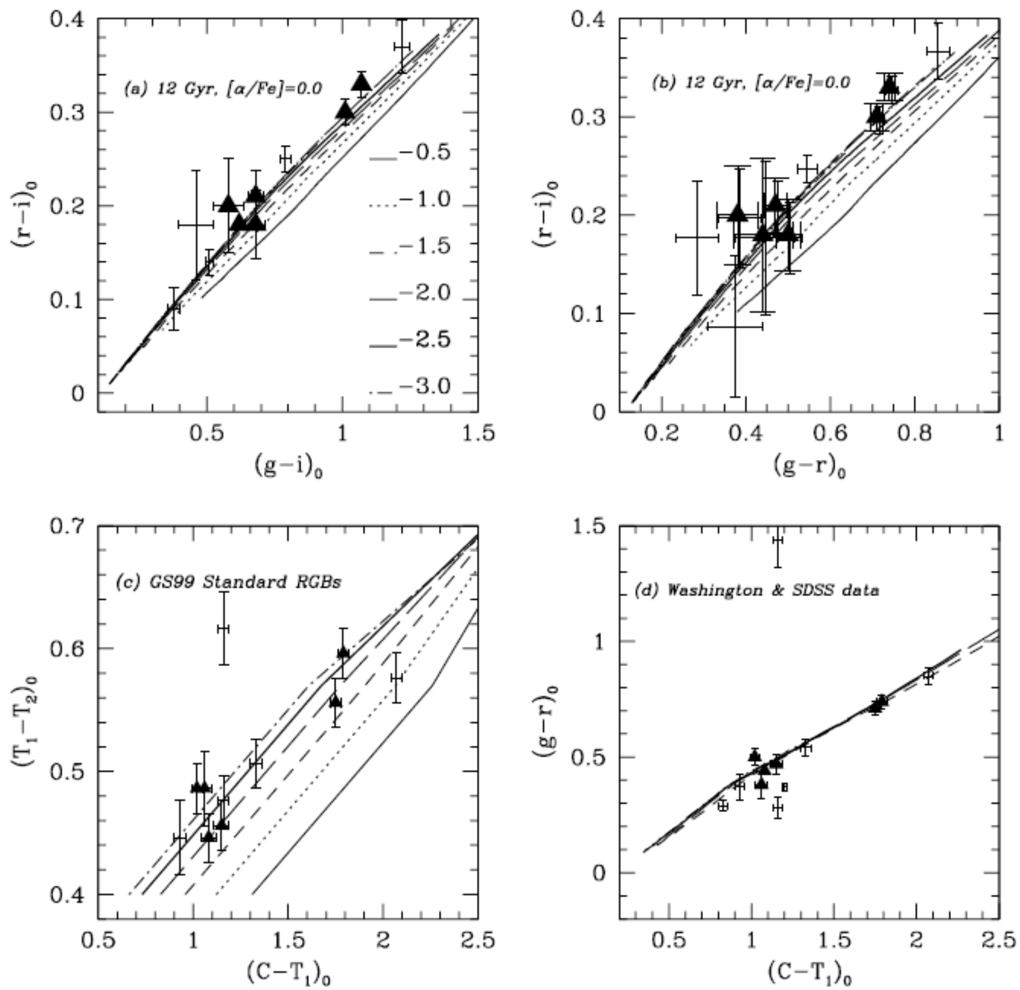
Color-color plots using a mixture of SDSS and Washington colors (Hughes, Wallerstein & Dotter 2011).

(a) $(r-i)_0$ vs. $(g-i)_0$ with Dartmouth models.

(b) $(r-i)_0$ vs. $(g-r)_0$ with Dartmouth models

(c) Washington colors with GS99 standard giant branches.

(d) Combining metallicity sensitive colors (g-r) and $(C-T_1)$ just results in a temperature and surface gravity index.

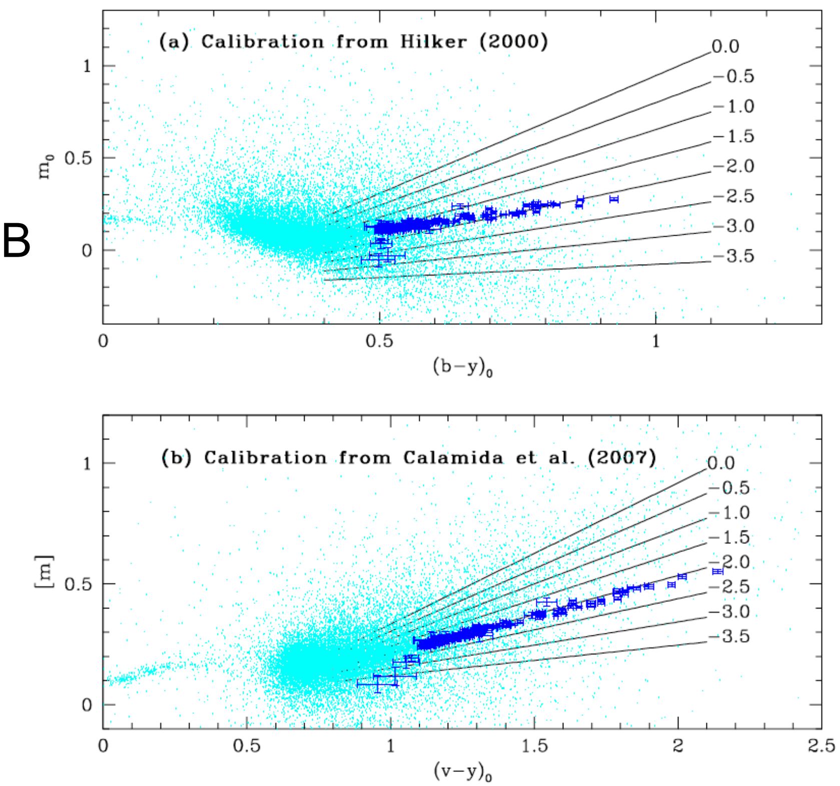


Q: Aren’t the Strömgren filters a better choice?

Strömgren color-color plots for M92

M92 is taken to have $(m\text{-}M)_V$=14.74, E(B-V)=0.025, [Fe/H]=-2.3 and [a/Fe]=+0.3, age ~ 11Gyr (Di Cecco et al. 2020).

A: Only above the HB



(a) $m_0=(v\text{-}b)_0\text{-}(b\text{-}y)_0$ for M92 RGB stars (blue points, Frank Grundahl, private communication), and the rest of the cluster stars (cyan).

(b) $[m]=m_1+0.3(b\text{-}y)$, the reddening-free index for the same stars. Calibration from Calamida et al. (2007).

The m_1 index separates field stars from dSph stars on the upper RGB, but the calibrations fail for stars below the HB

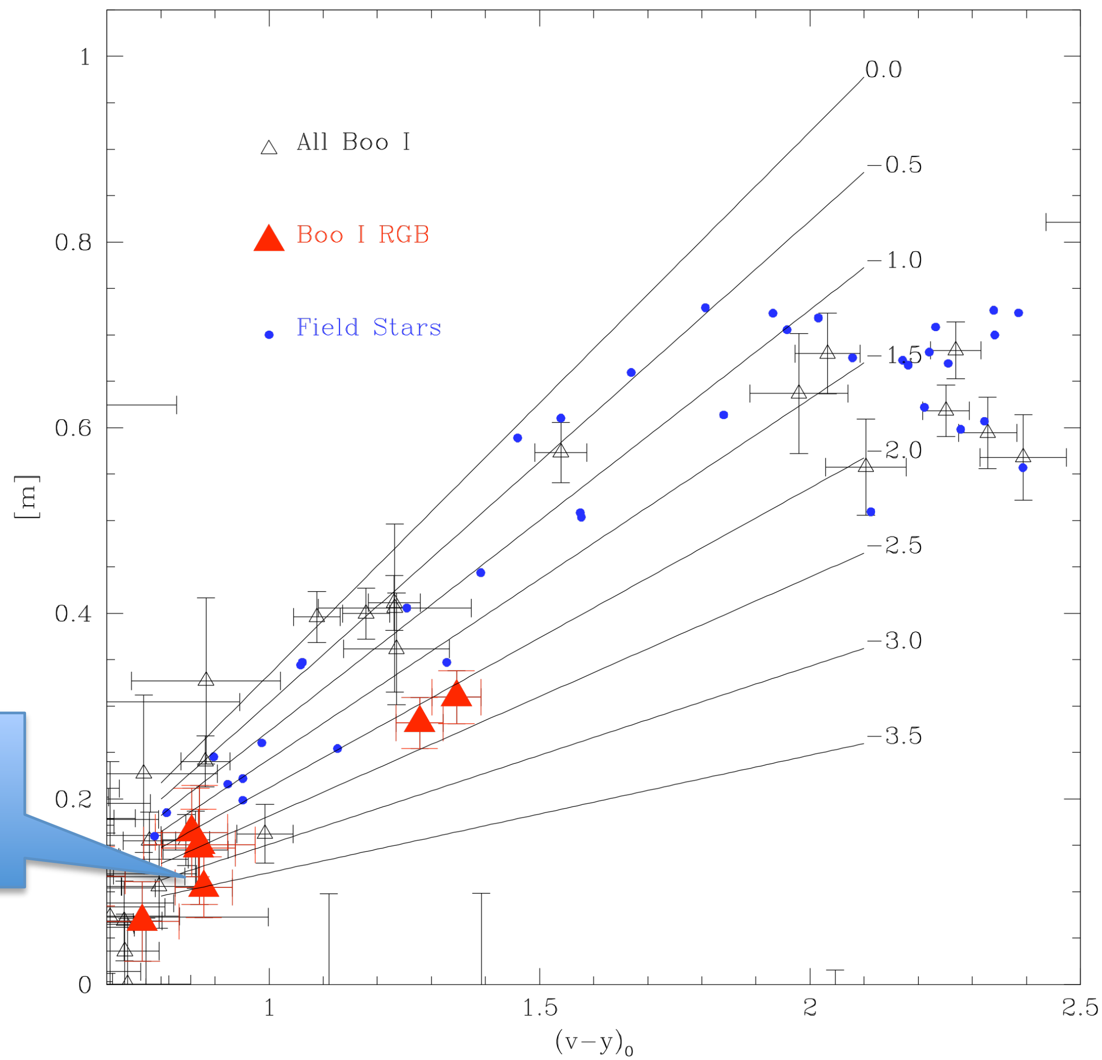
•Several groups have calibrated the Strömgren metallicity indices (e.g., Hilker 2000; Calamida et al. 2007; 2009) and find that calibrations fail for the RGB stars at ($b - y$) *< 0.5 for all schemes,*

•The m_1-index loses sensitivity as the line absorption in v becomes equal to the line absorption in b. In other words, the ***difference in line absorption between b and v becomes equal to the difference in line absorption between b and y***. As you get fainter on the RGB, the surface temperature rises and the lines get weaker (also see: Arnadottir, Feltzing & Lundstrom 2010, and references therein).

•The Strömgren filters are only better than Washington bands if you have plenty of upper RGB stars, or the system is close enough to have good photometry below the SGB, where the isochrones separate.

Strömgren color-color plot

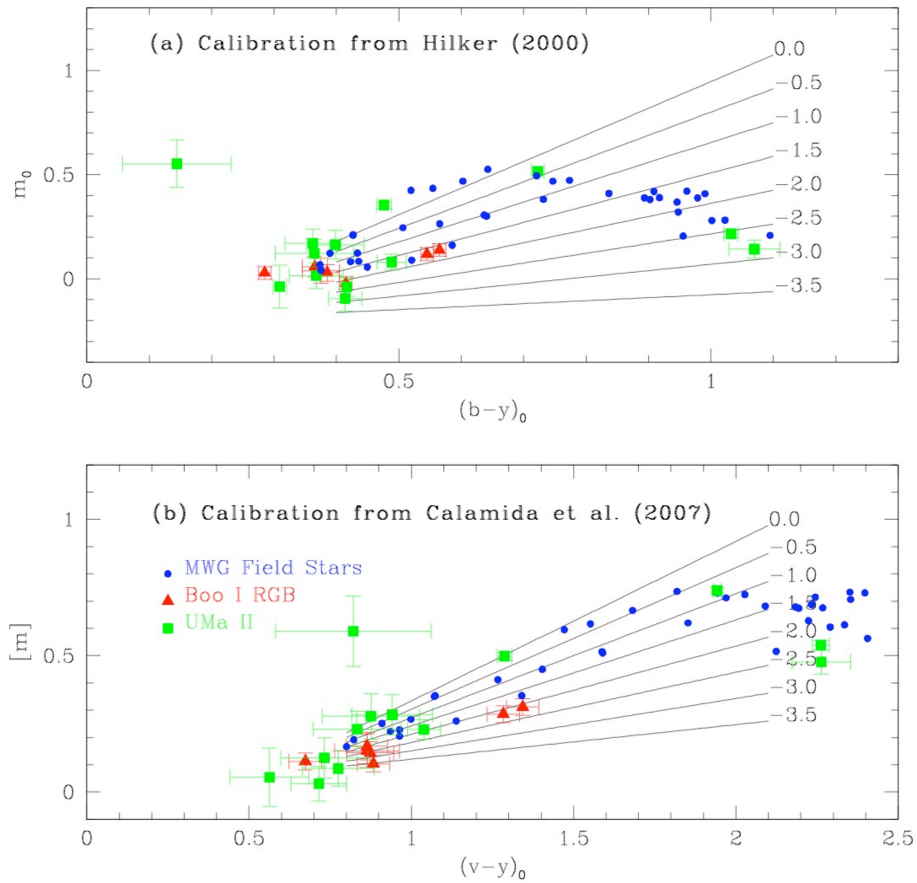
$[Fe/H] = -2.6 \pm 0.6$



Loses [Fe/H]-resolution for stars with log g > 2.5

[m] vs. $(v\text{-}y)_0$ color-color plot for the same data sets, with a [Fe/H] calibration from Calamida et al. (2007, ApJ, 670, 400). Here, $[m]=m_1+0.3(b\text{-}y)$ – the reddening-free index. We use their empirical calibration, based on selected globular clusters.

Strömgren color-color plots for the Boo I and Uma II dSphs

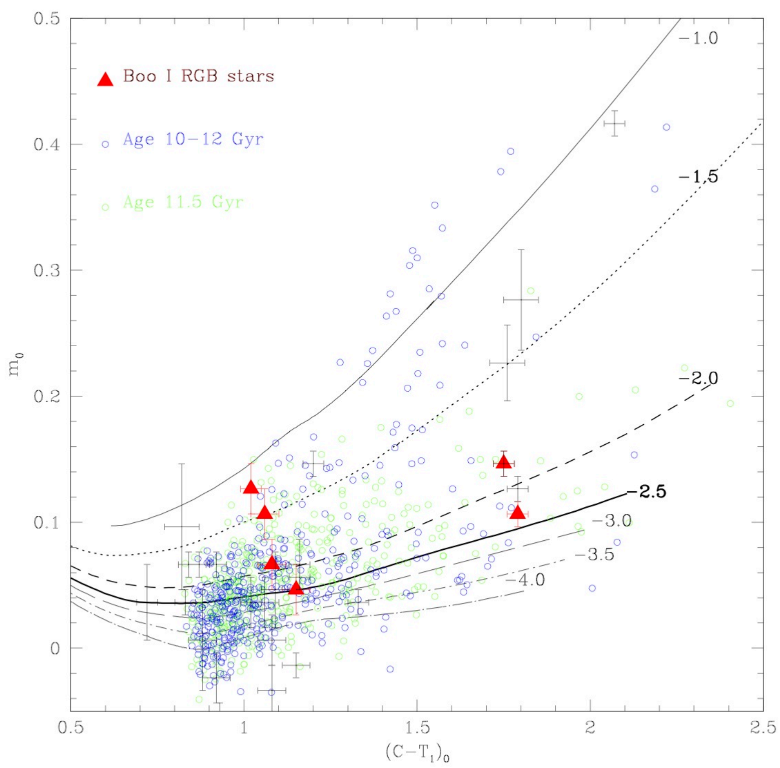


(a) $m_0=(v-b)_0-(b-y)_0$ for Boo I RGB stars (Hughes, Wallerstein & Dotter 2011; Norris et al. 2008; Martin et al. 2007), radial velocity-conformed RGB stars are red triangles (Martin et al. 2007). Artificial field stars are blue circles. Conversion to the [Fe/H] scale is given by Hilker et al. (2000). UMa II objects shown as green squares.

(b) $[m]=m_1+0.3(b-y)$, the reddening-free index for the same stars. Calibration from Calamida et al. (2007).

The m_1 index separates field stars from dSph stars on the upper RGB, but the calibrations fail for stars below the horizontal branch in both Boo I and Uma II.

Using vbyCT_1 filters: Boo I RGB stars and closed-box models

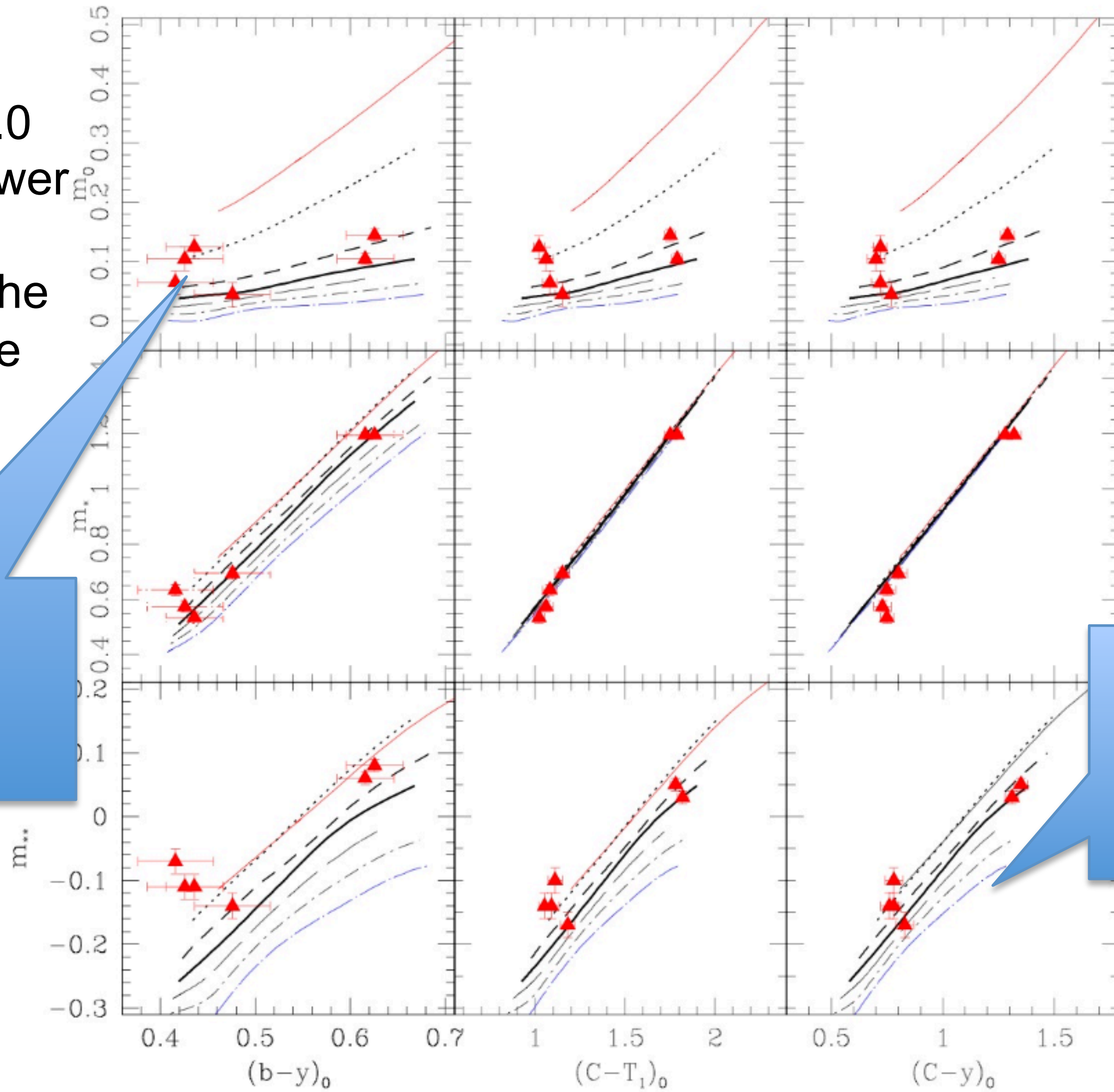


Green: Stars with -3.5<[Fe/H]<-1.5 and one burst of star formation 11.5 Gyrs ago.
Blue: : Stars with -3.5<[Fe/H]<-1.0 in one burst at 12 Gyrs and a slow tail of <10% of stars, up to 10 Gyr.

This plot gives best [Fe/H] Resolution but needs recalibration returns Hilker (2000) scale

$m_0=(v-b)_0-(b-y)_0$ $m_*=(C-T_1)_0-(T_1-T_2)_0$ $m_{**}=(C-b)_0-(b-y)_0$

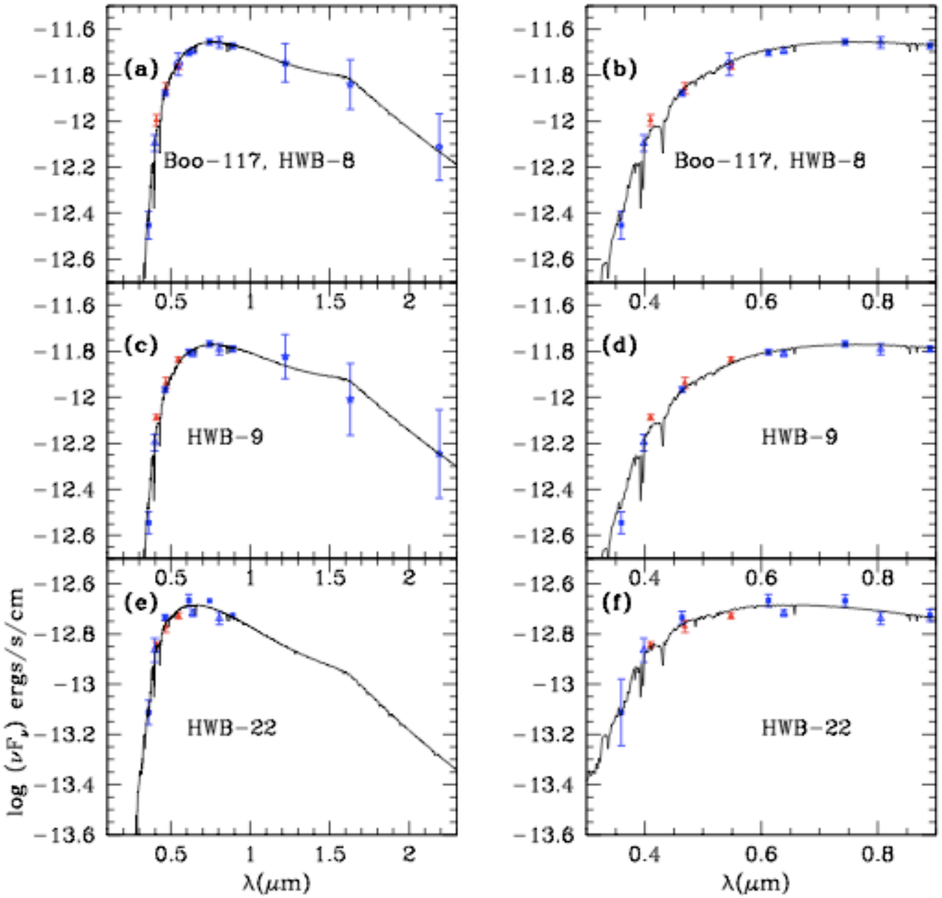
Lines are:
-1.0<[Fe/H]<-4.0
Upper left to lower right.
[Fe/H]=-2.5 is the heavy black line



Best for:
-1.0<[Fe/H]<-2.0

Replace v with C to gain S/N and if [Fe/H] < -2.0

Spectral Energy Distributions



The 3 brightest RGB stars from the Boo I field, using all available photometry, shown with the closest match from the stellar model grid (ATLAS9 database).

(a) and (b) Star 8 from HWB, model is [Fe/H]=-2.25, [α/Fe]=+0.2, T=4750K.

(c) & (d) Star 9, where model is [Fe/H]=-2.5, [α/Fe]=+0.2, T=4750K.

(e) & (f) Star 22, with model is [Fe/H]=-2.25, [α/Fe]=+0.2, T=5250K.

In all panels, vby filters are red filled triangles, CT_1T_2 are blue open triangles, SDSS filters are blue open squares & 2MASS magnitudes are blue stars.

Stars with known [Fe/H]

– find **$[Fe/H]_{Phot}$**[1] and break the age-metallicity degeneracy in CMDs – best fits to ATLAS9 models and Dartmouth Isochrones using $vbyCT_1$

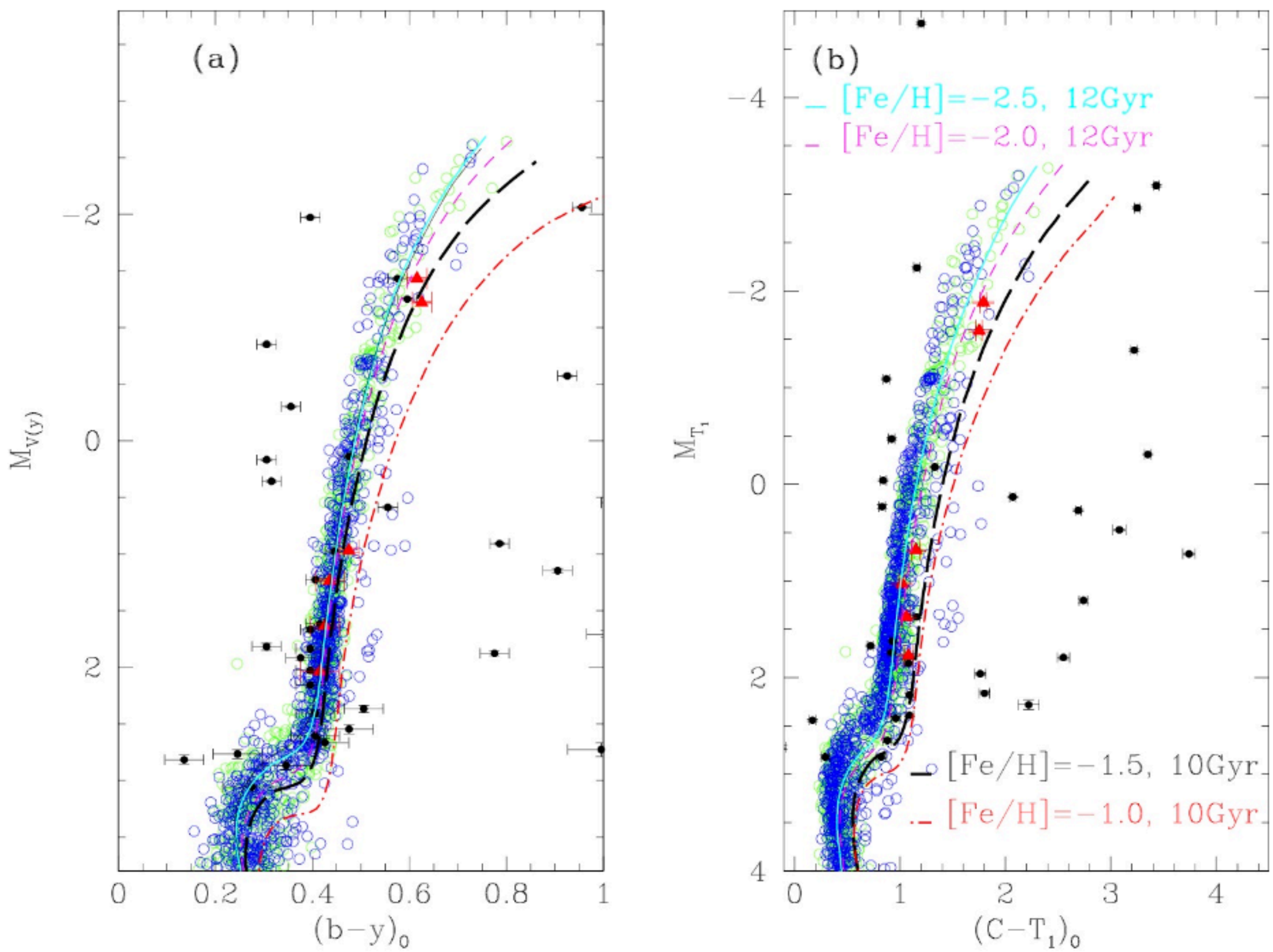
Star# (HWB)	$[Fe/H]_{Spec}$	$[Fe/H]_{Phot}$[1]	T_{eff}(K)	Log g	Age (Gyr)
8	-2.25	-2.25	4720	1.4	11
9	-2.7	-2.5	4760	1.5	12
22	-2.2	-2.6	5240	2.6	12
24	-1.9	-1.8	5300	2.7	12
28	-1.5	-1.5	5350	2.9	11
34	-1.3	-1.4	5380	3.1	12

(1) Uncertainties are < +/- 0.25 dex

(2) Star 8 is Boo-117 from Norris et al. (2008; 2010) and Feltzing et al. (2008).

Temperatures are +/- 50 K and ages +/- 1 Gyr. Found from the Dartmouth models. Radial velocity membership determined by Martin et al. (2007).

~Consistent with models with one burst of SF lasting less than 1 Gyr but enriching stars from [Fe/H]=-3.5 to at least -1.5.



Both the Washington and Strömgren Systems are effective for measuring [Fe/H], but (b-y) loses sensitivity on lower RGB. The (b-y)-color has better age resolution at MSTO.

Conclusions

•The Washington filters are better suited to dSph population studies than the Sloan filters because the (g-r) and (g-i) colors have less than half $(C-T_1)$'s sensitivity.

•The Strömgren photometry for the RGB is more sensitive to the metallicity than the Washington data for metal-poor systems on the upper RGB, BUT the dSphs's have so few upper RGB stars, we have to look for a better index than m_1 alone (also, it takes up to 5 times longer to get comparable S/N).

•Combining the m_1-index with the $(C-T_1)$ color allows individual stars to have $[Fe/H]_{Phot}$ measured to within 0.25 dex of spectroscopic values. Also, stars below the HB in distant dSphs are too faint for the *v*-band.

•Replace Strömgren-v with Washington-C.

Future Work

In 2007-11, we obtained data on 6 out of 8 SDSS-discovered dSph targets at APO in $vbyCT_1T_2$& the WLM dIrr. Leaman and Hughes are working on the WLM Mosaic II data from CTIO.

When the analysis is complete, we will have a database of age and metallicity for giant branch stars, independent of spectroscopy for systems inside the MWG's dark matter halo, and one outside our Galaxy's influence, as an isolated comparison.