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# An Absence of Gaps in the Main Sequence Population of Field Stars

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## ABSTRACT

Using high precision parallaxes from the Hipparcos catalog, we construct H-R diagrams for two samples of bright stars. The first is a magnitude-limited sample that is over 90% complete and uses uniform photometry from the Catalog of WBVR Magnitudes of Northern Sky Bright Stars ($\delta > -14^\circ$). This sample shows a smooth distribution of stars along the main sequence, with no detectable gaps. The second contains all of the stars closer than 100 parsecs in the Hipparcos catalog with $\delta < -12^\circ$. Uniform spectroscopy from the Michigan Spectral Survey shows that some stars which appear on the main sequence in the H-R diagram, particularly those in the $0.2 < B - V < 0.3$ region that has been labeled the Böhm-Vitense gap, are classified as giants by the MK system of spectral classification. Other gaps that have been identified in the main sequence are also affected by such classification criteria. This analysis casts doubt on the existence of the Böhm-Vitense gap, which is thought to result from the sudden onset of convection in stars. The standard identification of main sequence stars with luminosity class V, and giants with luminosity class III, must be reconsidered for some spectral types. The true nature of the stars that lie on the main sequence in the H-R diagram, but which do not have luminosity class V designations, remains to be investigated.

*Subject headings:* stars: fundamental parameters – HR diagram – Galaxy: stellar content

## 1. Introduction

Classical heat transport theory applied to stars suggests that fully stably-stratified radiative transport occurs for unevolved stars with hotter effective temperatures, while cooler stars have increasingly deep convective envelopes (e.g. Schwarzschild 1958). Astronomers have searched extensively for clear observational evidence of a transition region between those with radiative and those with convective upper layers.

In particular, Böhm-Vitense (1970) suggested that stars with convective atmospheres would be approximately 0.08 magnitudes redder in $B-V$ than stars with radiative upper layers for models with the same $T_{\rm eff}$, at least in the radiative-convective transition range. This implies that a population of main sequence stars with a continuous range of effective temperatures could exhibit a 0.08 magnitude jump in $B-V$ at some critical transition effective temperature $T_{\rm tr}$. This theoretical phenomenon has been referred to as the "the abrupt onset of convection" and the apparent gap is referred to as the Böhm-Vitense gap.

Although a gap was apparent in the local population of main sequence field stars as far back as 1953 (Johnson & Morgan 1953), Böhm-Vitense (1970) and Böhm-Vitense & Canterna (1974) first associated the gap with the onset of convection. Observations of this gap in the field population (Morgan, Harris, & Johnson 1953, Böhm-Vitense & Canterna 1974, Jasniewicz 1984) have generally been obtained by using spectroscopically determined luminosity classes to select only main sequence (luminosity class V) objects. For field stars the gap is typically in the $0.2 < B-V < 0.3$ range, which is consistent with the prediction of Böhm-Vitense (1970).

One would imagine that such a gap, as obvious as it is in the field population, would be easily detected in open clusters. Observations of open clusters, where cluster membership is determined by a combination of proper motion data, photometry, and spectroscopy, would alleviate any selection effects from using luminosity class separation alone. Such cluster observations, however, have produced ambiguous results. For example: Mendoza (1956) finds no gaps in the Pleiades, while Jasniewicz (1984), using stricter selection criteria, does note a gap. The latter author observes the position in color of the blue edge of the Böhm-Vitense gap to apparently differ with cluster age. Canterna, Perry & Crawford (1979) and Kjeldsen & Frandsen (1991) note that there are many different gaps, while Harris et al. (1993) find hints of a gap, but conclude that it may not be significant. Even Böhm-Vitense & Canterna (1974) do not see a gap in all clusters. Evidently, the statistical significance, location in color space, and density depression of the gaps appears to change from cluster to cluster.

One might account for the differing positions of the gaps in different clusters if rapid rotation of the stars in some clusters systematically retarded the onset of convection (Böhm-Vitense & Canterna 1974). Böhm-Vitense (1982) suggested that differing rotations, and thus different critical temperatures for the onset of convection, would cause a spread in a plot of $T_{\rm eff}$ vs. $B-V$. Based on a sample of about 50 stars, the paper finds evidence for two branches of late A and early F stars. Here, $T_{\rm eff}$ was determined from ultraviolet observations which probe higher atmospheric layers which were claimed by Böhm-Vitense (1982) to be a better predictor of a star's $T_{\rm eff}$ than the $B-V$ color index. Recently, however, Simon & Landsman (1997b) obtained more UV observations of A and F stars and find no evidence for a bifurcation in the ($B-V$, $T_{\rm eff}$) plane, and suggest that there may be no such phenomenon.

An alternate explanation of the apparent gaps is suggested by Figure 4 of Newberg & Yanny (1997). Here one can see two depletions in the distribution of over 3500 luminosity class IV and

V field stars: one at $B - V \approx 0.0$, and one at $B - V \approx 0.3$. These depletions are depicted to coincide with a relative excess of stars identified as luminosity class III. In this letter, we use the recent publication of the full Hipparcos data set (ESA 1997) to independently check the selection effects related to luminosity classification of nearby stars. In particular, we investigate whether systematics of the classification could be responsible for the gaps found by other authors.

## 2. Flux-limited sample – WBVR photometry

The Catalog of WBVR Magnitudes of Northern Sky Bright Stars (Kornilov et al. 1996, Kornilov & Mironov 1994) provides uniform and highly accurate photometry for 95% of the stars with $V < 7$ and $\delta > -14$ deg. Of the 9253 WBVR stars which match these criteria, 8896 stars have Hipparcos proper motions. The resulting catalog is a (90% complete) flux-limited sample of field stars with $M_V$ derived from parallaxes. The H-R diagram for this set of stars (Fig. 1a) does not show any gaps or under-densities in the $0.2 < B - V < 0.3$ region of the main sequence, but rather shows a smooth distribution of stars.

Over half of the stars (5717) have luminosity classes assigned to them. The H-R diagrams for luminosity class III, IV, and V stars for which luminosity classes exist are plotted in Fig 1 (b, c, d). Note that in Figure 1d there are depletions in the stellar density at $B - V \approx 0.3$ and at $B - V \approx -0.1$. It is clear from Figure 1b that luminosity class III stars fill in the $B - V \approx -0.1$ gap in the luminosity class V H-R diagram, but it is not clear what happened to the stars in the Böhm-Vitense gap. Examining the number of stars with luminosity classes as a function of $B - V$, we find that for stars preceding the gap on the blue side, 60%-80% have luminosity classes; for stars following the gap 60% have luminosity classes; but for stars in the gap, only 35%-40% are classified. Of the stars in the gap that do not have a luminosity class designation, 27% have spectral type Am or Ap. We will discuss the spectral classifications of the stars which fill the gap in more detail in the next section.

In order to demonstrate the existence of a gap, Böhm-Vitense & Canterna (1974) used a Aizenmann, Demarque & Miller (1969) diagram (rank ordered plot of stars' $B - V$) for a flux-limited sample of stars. They argue that *"For a narrow region of* $0.10 < B - V < 0.45$ *the main-sequence stars have a small range in mass so that we may expect a uniform distribution over masses and therefore over* $T_{\rm eff}$. *Any non-uniformity in the distribution over* $B - V$ *can then only be due to a nonuniform relation between* $T_{\rm eff}$ *and* $B - V$*."* We generate this rank diagram for luminosity class V field stars in Figure 2 (plotted as a thin line). With a factor of 20 more stars, we still find a depletion in stellar density in the $0.1 < B - V < 0.4$ range which is consistent with the results of Böhm-Vitense & Canterna (1974) and subsequent authors.

Main sequence stars might naturally be defined as those stars to the left of the Hertzsprung gap in the H-R diagram. We have approximated this division between main sequence and giants with the diagonal line in Figure 1a. We will refer to the set of stars with $M_V > 9.0(B - V) - 3.3$ as the “H-R main sequence” to distinguish it from the spectroscopic identification of luminosity class V stars. When one plots all H-R main sequence stars in the same rank diagram (Figure 2, heavy line), then there is no depletion observed, and thus no confirmation that there is a nonuniform distribution of $B-V$ for these stars.

## 3. Volume-limited sample – Houk spectral types

The Hipparcos data allows one to derive for the first time a color-magnitude diagram of a complete volume-limited sample of all stars in our solar neighborhood out to about 100 pc and down to fluxes of about $V < 9$. In addition, the Michigan Spectral Survey (Houk & Cowley 1975, Houk 1978, Houk 1982, and Houk & Smith-Moore 1988) identifies spectral types and luminosity classifications for essentially all stars in the southern hemisphere ($-90 < \delta < -12$), complete to about $V < 10$. Our volume-limited sample consists of 8156 stars with Hipparcos parallax $> 10$ mas and parallax errors typically $1\sigma = 1$ mas (stars with errors above 30 mas are excluded) that have been classified in the Michigan Spectral Survey.

Figure 3 shows the H-R diagram by luminosity class. The magnitudes used are those included with the Hipparcos Input Catalog (Grenon, Mermilliod, & Mermilliod 1992), and have photometric errors of typically 0.02 mag in $B-V$. Since the Houk classifications are essentially complete, we do not have the problems with missing giants or dwarfs that were apparent in Figure 1. It is apparent from Figure 3 that luminosity class III draws some A-F stars from the H-R main sequence population, leaving a well-defined gap in the luminosity class V H-R diagram.

Figure 4 shows the probability, as a function of $B-V$, that a star in the H-R main sequence will be assigned a given luminosity class. In the region $0.2 < B-V < 0.3$, only about 35% of the H-R main sequence objects are assigned to luminosity class V. The stars with missing classifications in the $B-V$ gap are primarily of type Am or Ap (a few are Fm or Fp) with no luminosity class assigned. Only about 5% of the luminosity class II/III, III, and III/IV stars in the gap have m or p designations. As noted by Hakkila & Mayer (1993) and Jasniewicz (1984), the metallic-lined A stars only partially fill the gap.

## 4. Discussion and Conclusions

The exquisite parallaxes obtained from the Hipparcos mission suggest a resolution to puzzling gaps seen in the main sequence of field populations and clusters. In fact, there are no gaps in the main sequence color-magnitude diagram afforded by Hipparcos parallaxes and precision photometry. Highly significant instances of the Böhm-Vitense gap are only found in studies where the sample of stars has been separated by luminosity class. The exclusion of spectral luminosity class III stars and stars with no luminosity class (such as those of type Am or Ap) depletes main sequence stars with $0.2 < B-V < 0.3$, leaving a density shortfall or gap. Unless these excluded stars are physically different from other main sequence stars and coincidently fill the gap, there is no gap caused by the sudden onset of convection.

The exact place in mass, temperature and $B-V$ color where stars change over from a radiative to a convective atmosphere remains undetermined from broad band photometry. Studies of stellar chromospheric activity, which is thought to be linked to convection, are also ambiguous (Simon & Landsman 1991, Simon & Landsman 1997a). It is interesting that Rachford (1997) finds a transition in the equivalent widths of the He I emission line at $B-V \approx 0.29$, indicating that this may be the boundary between radiative and convective stars. He notes that neither his activity indicator nor those using C II or X-rays can be used to separate stars in this color range by luminosity class, suggesting that the luminosity classes may have similar surface gravities.

The reason for the unexpected luminosity class identifications for late A stars remains to be investigated. Even when stars are separated by luminosity class, a gap is not found in every cluster. It is notable that investigations of different clusters can result in differing fractions of A star luminosity class identifications. For example, Mendoza (1956) classified 10 of the 11 stars in the $0.2 \leq B-V < 0.3$ region of the Pleiades as luminosity class V. The eleventh was metallic-lined. If the stars of the Pleiades were like those in the field, we would have expected only about four of the ten to be luminosity class V. Contrast this with Weaver (1952), who finds that out of fourteen A stars in the Coma Berenices cluster, eight are metallic-lined, four are peculiar and only two are class V dwarfs. The cluster to cluster population variation raises the possibility that spectral identifications for objects with $0.2 < B-V < 0.3$ are systematically influenced by physical factors such as age or metallicity (see Jasniewicz 1984).

The luminosity class III stars in Figure 3b which appear in the H-R main sequence may not be mis-classified. The goal of the MK system was not to determine physical properties of stars, but rather to present a consistent evaluation of their spectra (Morgan and Keenan 1973). We suggest that their interpretation as giant stars needs to be re-evaluated.

Other results which hinge on a uniform physical interpretation of the MK luminosity classes could be called into question. For example, bumps in the present day mass function, such as those noted by Scalo (1987), must be carefully examined to see if any selection on luminosity class was used to define the stellar sample. These bumps have been interpreted as evidence for a bimodal initial mass function or as inhomogeneities in the galactic star formation rate.

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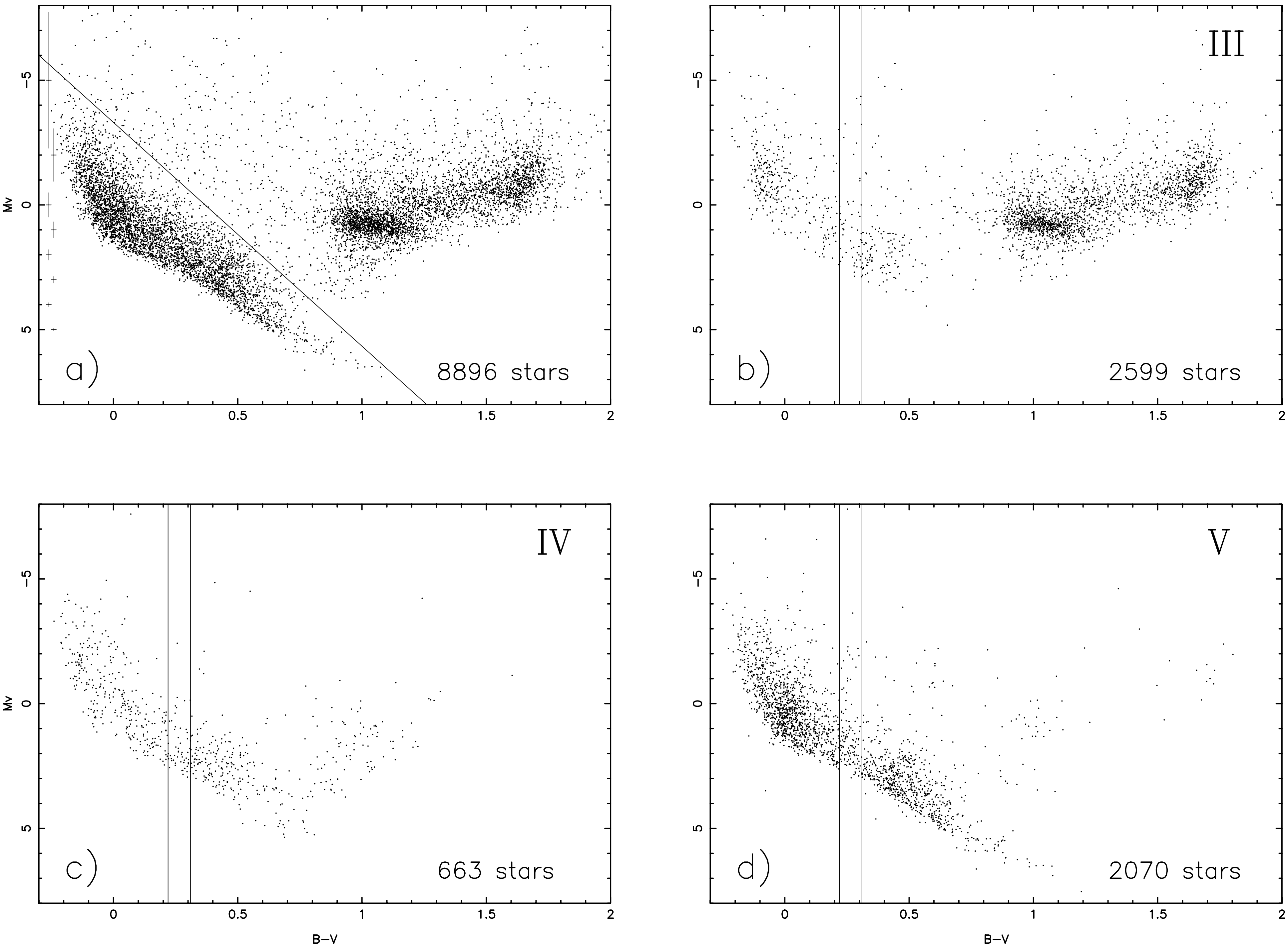
Fig. 1.— H-R diagram of field stars using parallax distances from Hipparcos, high accuracy WBVR photometry, and luminosity classes from the Hipparcos Input Catalog. (a) All stars in the flux-limited sample with $V < 7$. The sample is over 90% complete. We show the line $M_V = 9.0(B-V) - 3.3$ for reference. Approximate errors are given on the left side of the diagram. Errors in $B-V$ are due to the photometric errors in the WBVR catalog, which are typically 0.007 mags. Errors in $M_V$ are primarily due to errors in parallaxes measured by Hipparcos. For $7th$ magnitude and brighter stars, the Hipparcos satellite typically finds parallax errors of one mas. Approximate errors increase for intrinsically brighter objects since they are typically at larger distances in the magnitude-limited sample. Note the smooth distribution and absence of gaps at $B-V \sim 0.25$; (b) Luminosity class II/III, III and III/IV stars; (c) Luminosity class IV and IV/V stars; (d) Luminosity class V stars. The limits of the Böhm-Vitense gap ($0.22 < B-V < 0.31$), as measured by Böhm-Vitense and Cantera (1974), are shown as vertical lines. Note that only about 50% of the stars in this sample have luminosity class assignments in the Hipparcos catalog.

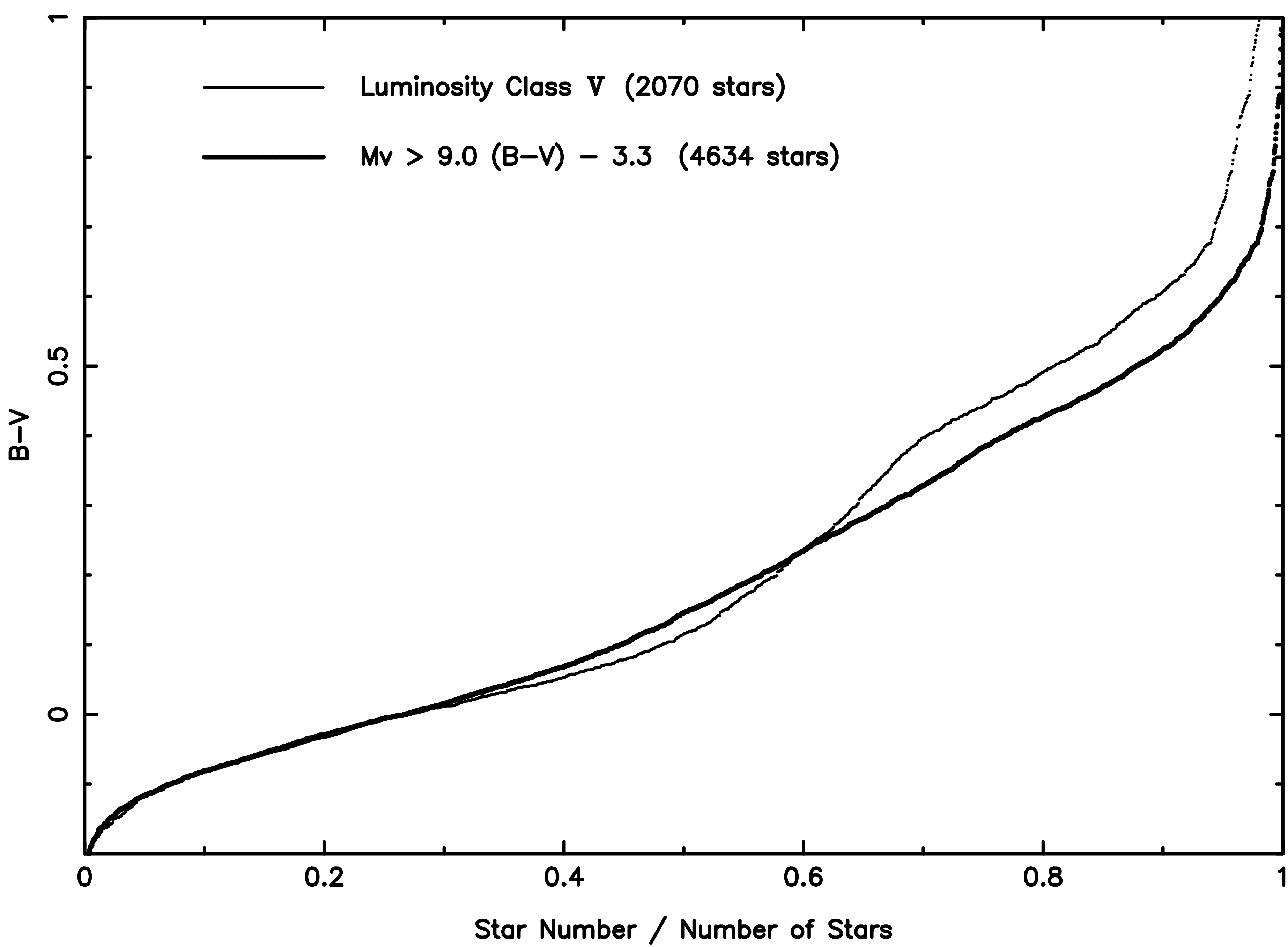
Fig. 2.— Cumulative distribution diagram in $B-V$ for luminosity class V field stars from Fig. 1(d) (thin line), and those of with $M_V > 9.0(B-V) - 3.3$ (thick line). The slope of the thick line is fairly constant over the range $0.10 < B-V < 0.45$, in contrast to the steeper slope of the thin line in the same range.

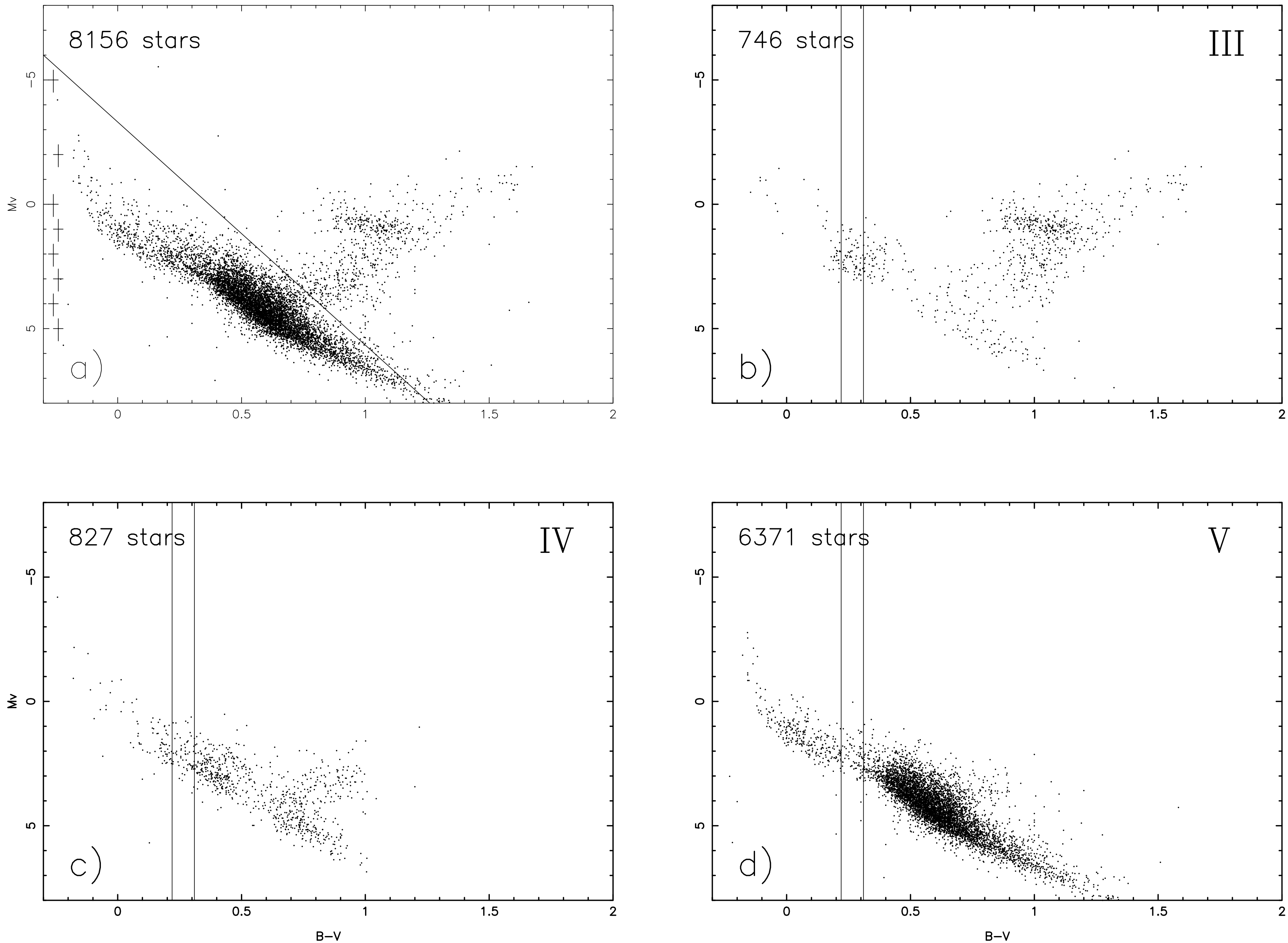
Fig. 3.— H-R diagram of field stars using parallax distances from Hipparcos, $B-V$ from the Hipparcos Input Catalog, and luminosity classes from the Michigan Spectral Survey. (a) All stars in the volume limited sample with $d < 100$ pc. Typical errors are shown on the left side of the diagram. Again, the photometric errors contribute very little to the errors in absolute magnitude, which are calculated assuming one mas parallax errors at 100 pcs. Again, the line $M_V = 9.0(B-V) - 3.3$ is shown for reference. (b) Luminosity class II/III, III and III/IV stars. (c) Luminosity class IV and IV/V stars, d) Luminosity class V stars. The limits of the Böhm-Vitense gap ($0.22 < B-V < 0.31$), as measured by Böhm-Vitense and Canterna (1974), are shown as vertical lines. In contrast to the stars in Fig. 1(a), all of the stars in Fig. 3(a) have MK classifications. Note that luminosity class III stars in b) tend to fill in the gap in the main sequence in d).

Fig. 4.— Fraction of stars in the H-R main sequence, as defined by $M_V > 9.0(B-V) - 3.3$, for three sets of luminosity classes. We include one sigma Poisson error bars (which are large on the blue end due to small number statistics). Most of the main sequence stars not included in the plot of II/III + III + III/IV + IV + IV/V + V are metallic-lined or peculiar stars; only a few have I or I/II designations. For example, in the interval $0.175 < B-V < 0.225$, 20% of the stars are luminosity class V, 31% have luminosity classes IV or IV/V, 28% have luminosity classes II/III, III, or III/IV, and 1% (not shown) have luminosity classes I or I/II. The remaining 20% are Am and Ap stars.

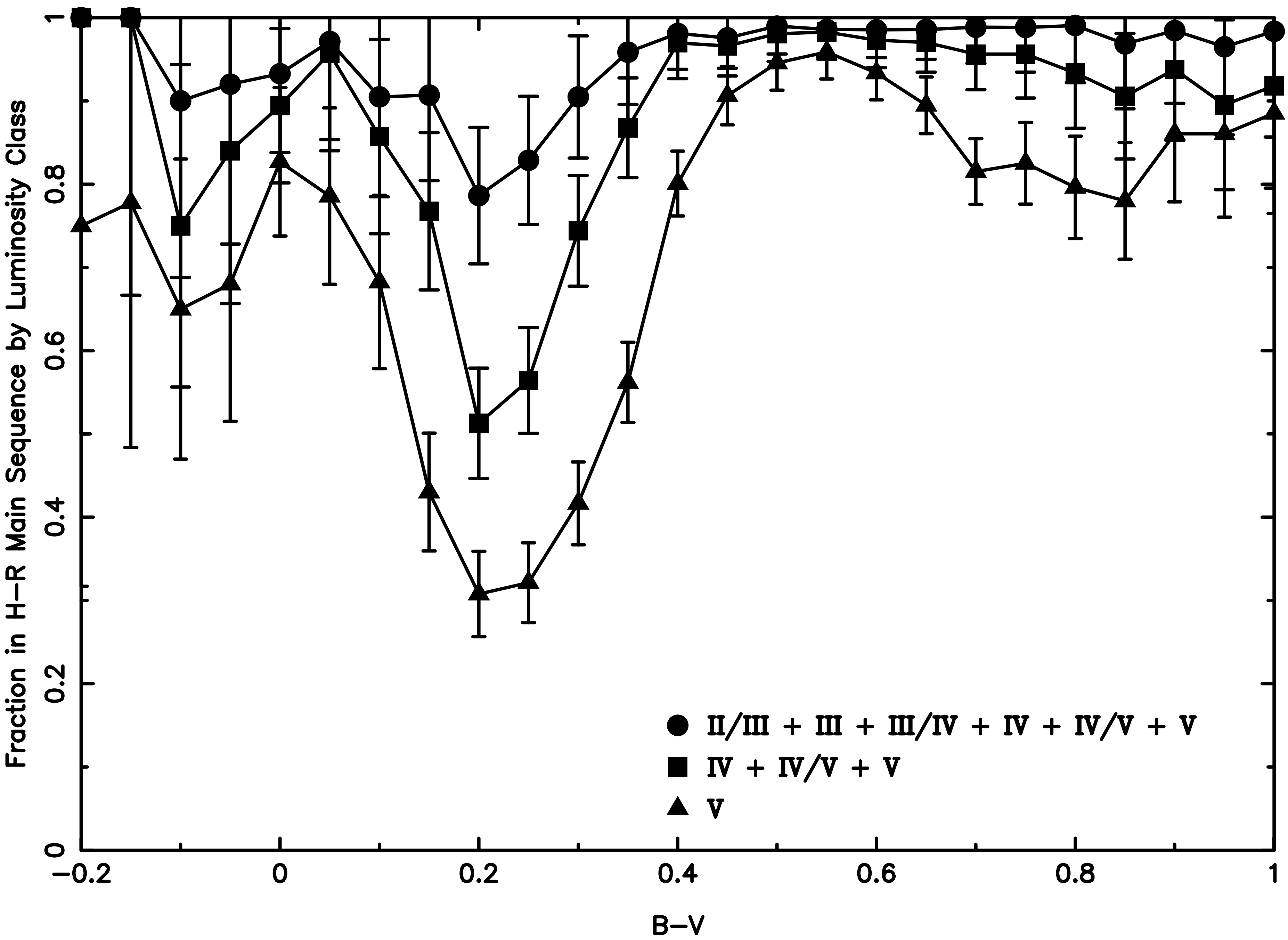


a)
8896 stars
b)
III
2599 stars
c)
IV
663 stars
d)
V
2070 stars
Mv
B−V


Luminosity Class V (2070 stars)
Mv > 9.0 (B−V) − 3.3 (4634 stars)
B−V
0
0.5
1
0
0.2
0.4
0.6
0.8
1
Star Number / Number of Stars



8156 stars
a)
746 stars
III
b)
827 stars
IV
c)
6371 stars
V
d)
Mv
B−V


Fraction in H–R Main Sequence by Luminosity Class
B–V
II/III + III + III/IV + IV + IV/V + V
IV + IV/V + V
V
0
0.2
0.4
0.6
0.8
1
−0.2