The Infrared Luminosity Function of Galaxies in the Coma Cluster

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ABSTRACT

An infrared survey of the central 650 arcmin^2 of the Coma cluster (Eisenhardt et al. 1998) is used to determine the H band luminosity function for the cluster. Redshifts are available for all galaxies in the survey with $H < 14.5$, and for this sample we obtain a good fit to a Schechter function with $H^* = 11.13 \pm 1.62$ and $\alpha = -0.78 \pm 0.24$. These luminosity function parameters are similar to those measured for field galaxies in the infrared, which is surprising considering the very different environmental densities and, presumably, merger histories for field galaxies. For fainter galaxies, we use two independent techniques to correct for contamination in the cluster population: the $J - K$ color-magnitude relation, and field counts. Using either method, we find a very steep upturn in the luminosity function for galaxies with $14.5 < H < 16$, with a slope of $\alpha = -2 \pm 0.3$.

Subject headings: galaxies: luminosity function, mass function — galaxies:clusters: Coma

1. Introduction

The availability of wide-field CCD detectors on large telescopes has renewed interest in the luminosity function of galaxies in clusters, which can now be determined to $M_B \sim -10$ at 100 Mpc, a luminosity limit comparable to that formerly reached in the Local Group (e.g., van den Bergh 1992). Coma, as one of the nearest ($z = 0.023$) and richest (R=2) Abell clusters is, together with Virgo, one of the best studied systems. As noted in Eisenhardt et al. (1998, hereafter EDGSWD) numerous CCD surveys have recently added to the large body of older photographic photometry (see also Mazure et al. (1998) for a compendium of recent work on the Coma cluster).

Optical luminosity functions for bright galaxies in Coma are consistent with a Schechter (1976) luminosity function:

$$\Phi(M)dM = \Phi^* 10^{0.4(\alpha+1)(M^*-M)} \exp(-10^{0.4(M^*-M)})dM$$

having $\alpha \sim -1$. Dwarf galaxies are better fit by a power-law of the form $N(M)dM \propto 10^{0.16M}dM$ (equivalent to $\alpha = -1.4$ in the Schechter formalism). These properties are similar to those of the luminosity function in Virgo (Sandage, Binggeli & Tammann 1985) and in Fornax (Ferguson & Sandage 1988). Recently, howewer, Lobo et al. (1997a) have claimed a steep V band slope for faint galaxies in Coma ($\alpha \sim -1.8$), supporting earlier claims for a large population of dwarf galaxies in clusters (e.g., De Propris et al. 1995). Table 1 summarizes recent determinations of the faint-end slope of the luminosity function in the Coma cluster.

It is generally difficult to relate optical luminosity functions to the underlying mass distributions, owing to our incomplete understanding of star formation in galaxies. Cold Dark Matter (CDM) models, with the Harrison-Zel'dovich ($n = 1$) spectrum favored by COBE data (Tegmark 1996), predict a galaxy mass function with a steep slope ($\alpha \sim -2$), although mergers are expected to deplete the low mass population in clusters (Dekel & Silk 1986; White & Frenk 1991). It has been known for some time that cluster galaxies have steeper LF's than in the field (Binggeli, Sandage & Tarenghi 1990), in contrast with the above predictions.

On the other hand, a steep optical LF may be compatible with a flat mass function if dwarf galaxies have their luminosities boosted by fading starbursts (Hogg & Phinney 1997). There is indeed some evidence for recent (1 – 2 Gyr ago) star formation among dwarfs in Coma (Donas, Milliard & Laget 1995) and in Virgo and Fornax as well (Held & Mould 1994 and references therein).

Infrared luminosities are known to be less sensitive to star formation and to correlate well with dynamical mass (Gavazzi, Pierini & Boselli 1996). Therefore infrared luminosity functions should be expected to approximate better the underlying mass function. A study of the infrared luminosity function of Coma is timely because of the recent publication of the first infrared-selected luminosity functions for field galaxies (Gardner et al. 1997, Szokoly et al. 1998), allowing a comparison of mass distributions in two environments of highly different densities. While Mobasher & Trentham (1998) have recently presented a K-band study of faint galaxies in Coma, their survey covers only 41 arcmin^2 and hence the luminosity function is not well constrained.

EDGSWD have obtained photometry in U, B, V, R, I, z, J, H and K_s for $\sim$ 500 infrared selected galaxies in a $29.2' \times 22.5'$ field in the core of the Coma cluster. EDGSWD selected objects at H (and required confirmation at J) to provide a baseline for comparison to K selected samples in more distant clusters (Stanford, Eisenhardt & Dickinson 1995, 1998), and also because the H data reached approximately 0.5 mag deeper. Here we use this data to derive the H luminosity function for galaxies in the Coma cluster. The conversion from H to K_s is provided in §3.1. A detailed description of the data, observations, data reduction and photometry is given in EDGSWD, and is not repeated here, except for some essential points. We assume a redshift of 6950 km s^{-1} (Mazure & Gurzadyan 1998).

2. The Luminosity Function

Star-galaxy separation was determined in the R band using the Kron (1980) r_{-2} parameter (EDGSWD). Figure 1 plots the infrared color-magnitude relation for galaxies in the EDGSWD catalog. To determine the luminosity function we must correct for non-cluster members. Because the available membership information is qualitatively different for bright vs. faint galaxies, we consider them separately. After correcting for membership as described below, galaxies were counted in 0.5 magnitude bins. The resulting luminosity function is shown in Figure 2.

2.1. Bright Galaxies

For galaxies with $H < 14.5$ redshifts are available in the literature (Lobo et al. 1997b). All galaxies with $3000 < cz < 10000$ km/s are assumed to be members and at the same distance.

For bright galaxies we choose to fit a Schechter function, using a downhill simplex algorithm, where errors are calculated by using a bootstrap resampling technique (Press et al. 1974). The best fitting parameters are $H^* = 11.13 \pm 1.62$ and $\alpha = -0.78 \pm 0.24$. Note that the three brightest objects are excluded from the fit, since we are unable to fairly sample their space density and such objects fall outside of the extrapolation of the Schecter function at bright magnitudes (Schechter 1976; Lugger 1986).

To illustrate the uncertainty in H^* and α, a series of Monte Carlo simulations were generated in which 1000 objects were drawn from a Schechter function whose parameters were the best fit to our 'original' data. These artificial data were fitted using the same method as above, and the results are shown as an inset in Figure 2.

2.2. Faint Galaxies

For fainter galaxies ($14.5 < H < 16$) we use two independent methods to correct for non-cluster members. Following Mazure et al. (1988) and Biviano et al. (1995), we assume that galaxies within ±0.3 magnitudes of the color-magnitude relation defined by the brighter early type galaxies are members. The relation and the color selection criterion are shown in Figure 1. Our selection is in $J - K$, while Mazure et al. and Biviano et al. select in $b - r$, but available spectroscopy for the faint sample (shown in Figure 1) supports this criterion. We also use the infrared counts by Gardner, Cowie & Wainscoat (1993) transformed to the H band using our color-magnitude relation in $H - K$, to remove contamination by a simple background subtraction technique.

As shown in Figure 2, both the color selection method and the background subtraction method result in a significant excess of faint galaxies relative to the Schechter function for bright galaxies determined above. Fitting to the color selected values plus the $14 < H < 14.5$ bin yields $\alpha = -2 \pm 0.3$. It is perhaps worrisome that this excess occurs at just the point where assigning membership becomes uncertain. Could this slope be an artifact?

Magnitude errors and spurious detections can cause an artificial steepening in the derived slope (Kron 1980). However, the estimated errors are smaller than the width of the bin even for the faintest galaxies considered, and spurious detections should be few because objects were required to be detected in both the J and H images. In fact we are quite likely to have *underestimated* the number of dwarfs due to the difficulty in detecting low surface brightness galaxies against the bright infrared background. The completeness is estimated from Monte-Carlo simulations to be $> 80\%$ to $H = 16$ for galaxies with $r_1 < 1.4h^{-1}$ kpc and $> 90\%$ to $H = 16.5$ for $r_1 < 0.7h^{-1}$ kpc (EDGSWD), where r_1 is the first moment of the light distribution (Kron 1980). Because Fornax cluster dwarfs typically have effective radii $< 1h^{-1}$ kpc (Ferguson 1989), we do not expect this to be a large correction.

Misclassifying stars as galaxies cannot account for the upturn: there are no significant discrepancies in star/galaxy classification between EDGSWD and Lobo et al. 1997a, and comparison with star counts in the Bahcall & Soneira (1980, 1981) models shows good agreement.

A more serious concern is that the slope of the infrared background counts is similarly steep (equivalent to $\alpha = -2.7$, Gardner et al. 1993), raising the possibility that an incorrect removal of contaminating objects is responsible for the upturn. We consider this unlikely because (i) counts obtained via color selection agree well with those derived via background subtraction techniques; (ii) the excess required to account for our result is a factor of 3 above the estimated background and foreground counts; and (iii) galaxy counts in the direction of the Coma cluster are found to be in satisfactory agreement with those in the general field (Secker & Harris 1996). Deep redshift surveys in the field of the Coma cluster have revealed the presence of some background structure, possibly identified with a cluster at $z = 0.5$ (Secker et al. 1998), but our color selection should exclude such objects. The typical color of cluster galaxies at $z = 0.5$ is $J - K \sim 1.6$ (Stanford et al. 1998), which is 0.5 magnitudes redder than the red edge of our color 'cut'.

Nevertheless, the question of cluster membership for these galaxies is the dominant uncertainty in our measurement of the faint end slope, and we are planning on a redshift survey of the faint sample, in order to address the issue of their membership. Time has already been awarded on the WIYN telescope to pursue this investigation.

3. Discussion

3.1. Bright Galaxies

The infrared luminosity function derived for bright galaxies ($H < H^* + 3$) is in good agreement with that at R (Lopez-Cruz et al. 1997) as well as at V (Lobo et al. 1997a): all are reasonably well matched by a Schechter function with a 'flat' ($\alpha \sim -1$) power law. This argues for a relatively small contribution from young stars in these galaxies.

Using the observed $H - K_s = 0.22$ and a k-correction of +0.05 we obtain $M_K^* = -23.25 + 5\log(h)$, in excellent agreement with the $-23.12 + 5\log(h)$ value reported by Gardner et al. (1997) for their field sample. Using the observed $B - H = 4.2$ yields $M_B^* \approx -19.1 + 5\log(h)$, vs. $M_B^* = -19.0 + 5\log(h)$ for the Virgo Cluster (Sandage et al. 1985). The agreement is somewhat fortuitous given the uncertainty in H^* due to our smaller sample and the fact that we do not properly survey the brightest galaxies. The -0.78 ± 0.24 slope of the bright portion of the Coma IR luminosity function is also in good agreement with the $\alpha = -0.91 \pm 0.21$ value of Gardner et al. (1997) seen at the same absolute magnitudes. Our result may be influenced by the presence of a 'dip' seen in the optical luminosity function of Coma at $V \sim 17$, equivalent to $H \sim 14$ (Lobo et al. 1997a). The IR luminosity functions (and hence mass functions) of bright galaxies in the field and in this rich cluster appear to be similar, despite the roughly thousand-fold difference in environmental density. This agreement is surprising because of the different morphological mixes and, presumably, merger histories for these galaxies. If mass is truly the defining parameter in controlling the bulk properties of galaxies and their morphology (see Gavazzi et al. 1996) this similarity supports models in which large galaxies form at high redshift and evolve passively to the present epoch, and in which mergers are relatively unimportant (a scenario also favored by Stanford et al. 1998).

3.2. Faint Galaxies

For galaxies fainter than $H = 14.5$, we find a steep upturn in the luminosity function ($\alpha \approx -2$). Due to the uncertainty in cluster membership, this result should be considered to support claims for a steep luminosity function for dwarfs, rather than providing a precise estimate of the slope of the faint end of the luminosity function. Nevertheless, we detect a population of dwarfs about two times larger than expected from an extrapolation of a Schechter function with $\alpha = -1.4$ (Bernstein et al. 1995; Lopez-Cruz et al. 1995; Secker et al. 1997).

Because H luminosity is linearly correlated with mass for field and Virgo cluster galaxies (Gavazzi et al. 1996), the most natural interpretation of the steep infrared slope is that it represents a real increase in the space density of low mass galaxies in Coma, rather than an enhanced star formation rate in such objects.

There is some suggestion in Table 1 that the luminosity function slope increases with clustercentric radius (e.g. Lobo et al. 1997a). Such a trend might be caused by a higher incidence of mergers or tidal disruption in the dense cluster core. On the other hand dwarfs may actually *form* in mergers (Krivitsky & Kontorovich 1997) and in tidal tails (Hunsberger, Charlton & Zaritsky 1996). The reality of the trend towards steeper slopes at larger radii remains inconclusive: Lopez-Cruz et al. (1997) and Secker et al. (1997) find $\alpha = -1.4$ at R in fields of similar size to ours, identical to the value found at R by Bernstein et al. (1995) in a small field near the cluster center.

Another possibility is that most of the luminosity from dwarf galaxies comes from fading bursts of star formation, leading to steeper faint end slopes at longer wavelengths, as predicted by Hogg & Phinney (1997). Because the burst luminosity becomes fainter and redder with time, there is an increased probability of finding faint, red galaxies. Given the difference in mass to (near infrared) light ratio of a 10^8 vs. a 10^{10} year old population

(Bruzual & Charlot 1993), starbursts producing $\sim$ 10% of the mass in the underlying population every few hundred million years would satisfy the requirements of the Hogg & Phinney model. Although some Fornax cluster dwarfs show evidence for a substantial young population (Held & Mould 1994), none of the Local Group dwarfs, with the possible exception of the Fornax dwarf (Gallagher & Wyse 1994) show such evidence. Again, existing data on the correlation of slope with wavelength are inconclusive (Table 1).

It is also plausible that the dwarf galaxy H luminosity function is more accurately a Schechter function than a power law, and the steep slope we measure is only an approximation to the exponential portion of the function. Binggeli et al. (1988) suggest $M_B^* = -15.9 + 5\log(h)$ for dwarfs, corresponding to $H \approx 15.5$ in Coma. In this case the data of Mobasher & Trentham (1998), which samples a smaller field to $K = 18.5$, provides a better estimate of the faint end slope.

A comparison with field dwarfs is difficult, since no infrared survey has yet reached luminosity limits as deep as ours (which is equivalent to $M_K \sim -18.5 + 5\log(h)$). Using a K_s-selected sample with 110 redshifts, Szokoly et al. (1998) do find a steeper slope ($\alpha \sim -1.3$) in their field infrared luminosity function than Gardner et al. (1997), despite the similar luminosity limit ($M_K \sim -21 + 5\log(h)$) of the samples analyzed, but we consider Gardner et al.'s result more reliable as it is based on $\sim$ 500 redshifts. If the similarity between the IR and optical luminosity functions in Coma also holds true in the field, the very steep slope ($\alpha \sim -2.8$) found by Loveday (1997) at b for faint galaxies in the Stromlo-APM survey may foretell an upturn in the IR field luminosity function as well. The 2MASS survey should settle this issue, as it will reach $M_K \sim -16.5 + 5\log(h)$ at the distance of the Virgo cluster (Skrutskie et al. 1997).

Our results for Coma support the existence of an universal galaxy luminosity function, which is well approximated by a flat Schechter function for bright galaxies and a steep power-law for dwarfs (Trentham 1998b). As demonstrated by EDGSWD and Skrutskie et al. (1997), it is now possible to obtain 'panoramic' data in the infrared: Other clusters should now be studied with the same methods, in order to determine the mass function of galaxies in clusters and study the effects of their environment.

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LIST OF FIGURES

Figure 1 - $J - K$ vs. H color magnitude diagram for galaxies in the field of the Coma cluster. Filled circles are spectroscopic members, open squares spectroscopic non members, and crosses objects for which spectroscopy is not available. The thick solid line shows the empirical color magnitude relation for bright E and S0 galaxies. The dashed lines show the limits of the color criterion used to assign membership.

Figure 2 - The luminosity function of the Coma cluster and the best fitting Schechter function (solid line). Brighter than $H = 14.5$ galaxy membership is determined spectroscopically. For fainter galaxies we use both the color magnitude relation (open circles) and background counts (crosses). The 'power law' with slope of -2 is shown as a dashed line for illustrative purposes. The differences between the values of H^* and α retrieved from Monte Carlo simulations and the best fit values are plotted in the inset.

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TABLE 1

RECENT MEASUREMENTS OF THE SLOPE OF THE FAINT END OF THE COMA LF

Field Size (□′)	α	Mag. Range	Reference
14300	-1.32	$17.0 < b < 20.0$	1
1200	-1.3 ± 0.1	$13.0 < b < 20.0$	2
51	-1.51 ± 0.13	$16.5 < V < 21.0$	3
1500	-1.80 ± 0.05	$13.5 < V < 21.0$	3
674	~ -1.7	$20.0 < R < 24.0$	4
52	-1.42 ± 0.05	$15.5 < R < 23.5$	5
529	-1.42 ± 0.12	$R < 22.5$	6
700	-1.41 ± 0.05	$15.5 < R < 22.5$	7
657	-2.0 ± 0.3	$14.0 < H < 16.0$	8
41	-1.41 ± 0.35	$15.5 < K < 18.5$	9

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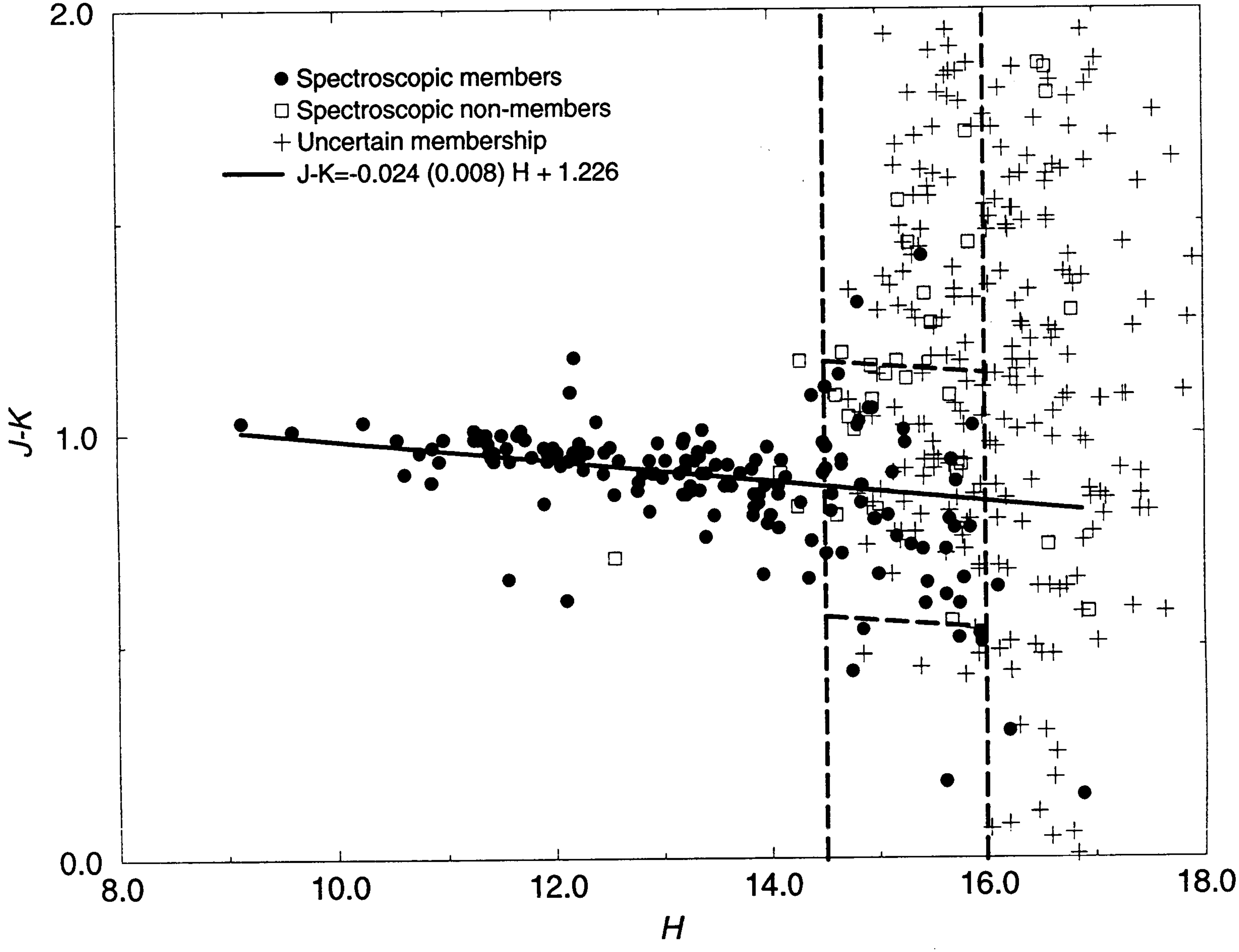
● Spectroscopic members
□ Spectroscopic non-members
+ Uncertain membership
J-K=-0.024 (0.008) H + 1.226
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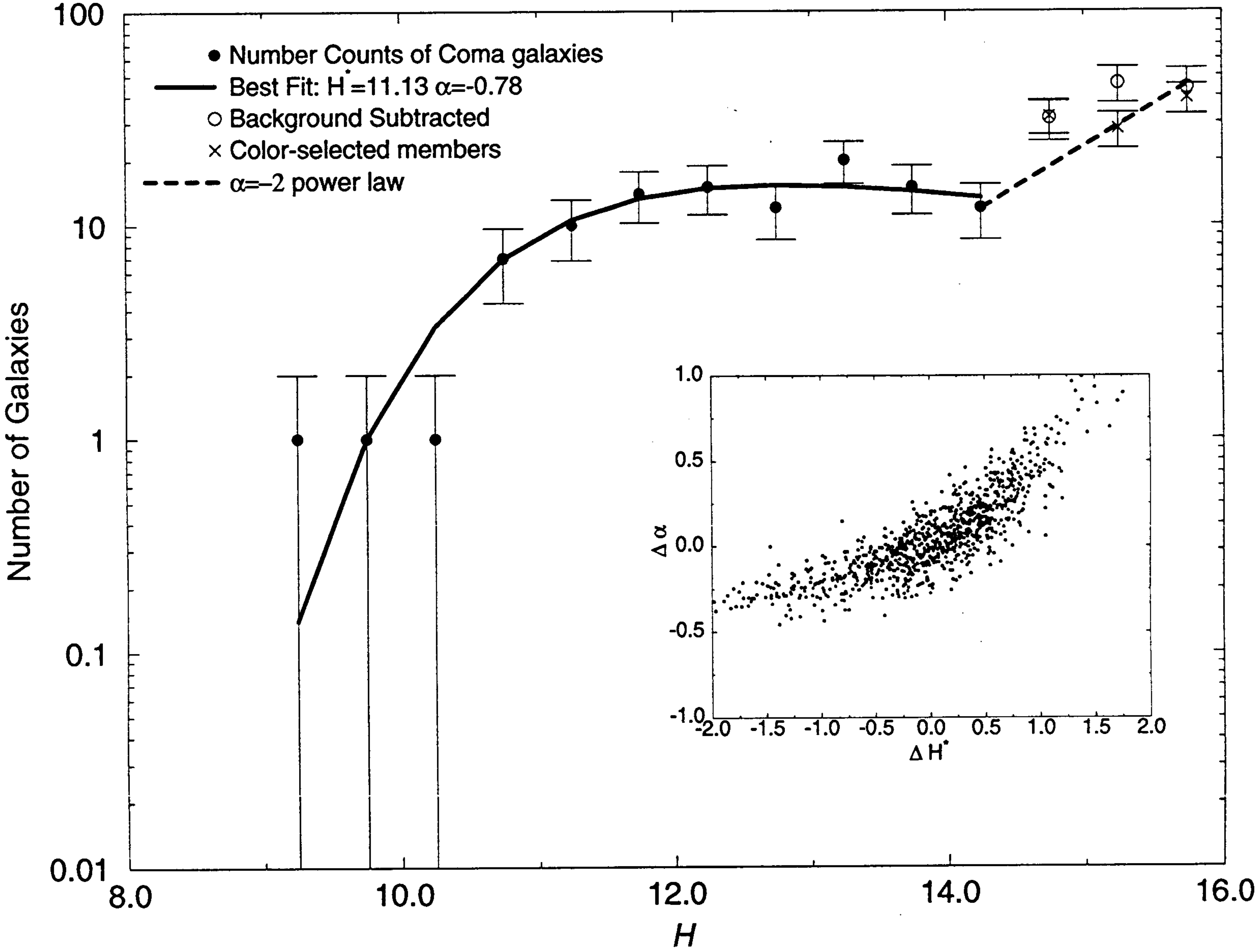
1.0
0.0
J-K
8.0
10.0
12.0
14.0
16.0
18.0
H



● Number Counts of Coma galaxies
Best Fit: H^*=11.13 α=-0.78
○ Background Subtracted
× Color-selected members
α=−2 power law
Number of Galaxies
H
100
10
1
0.1
0.01
8.0
10.0
12.0
14.0
16.0
Δ α
Δ H^*
1.0
0.5
0.0
-0.5
-1.0
-2.0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0