Evidence for Low Mass Star Formation in Cooling Flow Galaxies

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Abstract

Evidence is presented based on narrow band optical and near-l R imaging that field and cluster cooling flow galaxies are enriched in low mass stars, the result of recent, truncated IMF star formation from accreting gas. Galaxies with low accretion rates (M <5 $M_{\odot}$ yr^{-1}) have normal optical colors and gradients, but red $V - K$ colors signaling an IMF enhanced in low mass main sequence stars. Cluster cooling flow elliptical ($\dot{M}$ >50 $M_{\odot}$ yr^{-1}) display characteristics of weak bursts in star formation (i.e. blue optical colors), but at an efficiency which places only **.5%** of the accreting matter into an IMF similar to that found in tile Galactic disk. Red $V - K$ colors arc also found in cluster galaxies indicating that the remaining mass is again sited in low mass stars.

I. Introduction

Space observations in the early 1980's demonstrated the presence of massive, hot x-ray halos around field and cluster early-type galaxies (Forman, Jones and Tucker 1985, Canizares, Fabbiano and Trinchieri 1987). The x-ray emission arises by thermal bremsstrahlung with average temperatures ranging from 3 x 107 to 10^8 K and masses for the gas which rivals the luminous mass in stars. Evidence based on x-ray emission lines, high central surface brightness from x-ray continuum imaging and the detection of strong Faraday rotation in the cores of the central galaxies, suggests that the x-ray gas is cooling and that the cooling times arc much less than $1/H_o$ producing a flow of accreting gas (Nulsen, Stewart and Fabian 1984).

Detection of 111 and CO in cooling flow galaxies confirms the existence of accreting gas (McNamara, Bregman and O'Connell 1990). However, the amount detected is much smaller than the amount predicted from the cooling rates. Onc explanation for the missing gas is to turn it into stars for, as the accreting gas flows inward, the density rises and there exists the possibility of star formation from which an "accretion" population of stars (AP) would arise (see Fabian 1988 for a review). Emission lines have been detected in several cooling flow galaxies, most notably NGC 1275, indicating the existence of hot gas (McNamara and O'Connell 1989). However, evidence of hot gas is not equivalent to evidence of star formation and the production of an A 1'. For example, mass loss in bright ellipticals is typically 0.1 to 0.5 $M_{\odot}$ yr^{-1}(Faber and Gallagher 1976). This gas, combined with a source of UV photons such as PAGB stars, would produce the kind of Hα emission that has been detected in many ellipticals (Bertola *et al.* 1991).

Some cooling flow galaxies do display other indicators of star formation and a young stellar population such as blue excess (McNamara 1991). Yet, there still exists large discrepancies between the cooling rates, the expected amount of accumulated gas and the amount of star formation implied by the colors and emission line strengths. For example, the accretion rates in cooling flow galaxies ranges from $1 M_{\odot}$ yr^{-1} for isolated, field ear]y-type galaxies to over 100 $M_{\odot}$ yr^{-1} for several cluster cooling flows and, averaged over a Hubble time, would imply amounts of cool gas that would produce an Al' supplying from 10% to 100% of the luminous matter in early-type galaxies. If the gas were turned quickly and efficiently into stars with an IMF similar to the Galactic

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IMF, to account, for the lack of large amounts of cool gas ($10^{9}A4_{0}$), then a starburst would occur in each cooling flow early-type galaxies at a strength that would rival many ultraluminous galaxies. Since an excess of UV and blue light due to massive stars is not commonly observed, nor is the cooling flow deposited in the form of neutral gas, then some mechanism is required to disguise or hide the accretion population or to interrupt the formation of cool gas.

Several mechanisms to disrupt the cooling gas are considered and dismissed (see McNamara 1991) such as heating of the gas by SN or gravitational collapse. Hiding the star formation by dust would produce dust lanes that arc' easily visible as extinction in optical bandpasses or strong far-IR emission detectable by IRAS. One is left with the remaining conclusion that if the accreted mass is turned into stars then the IMF of the AP must be tailored to match the optical colors of early-type galaxies, i.e. one truncated at the high mass end to avoid the production of blue and UV photons by hot photospheres. 'J'he purpose of this study is to use a narrow blue system of filters (Strömgren *uvby*) to determine the color indices around 4000Å (a region dominated by the light from subgiants and dwarfs near turnoff) and compare them to near-IR colors (where the light from cool giants dominates). If a recent accretion population exists with colors which do not *exactly* mimic an old, giant dominated population, then the baseline from 3500Å to 2.2μm would be the most sensitive to such a detection.

I 1. observations and Results

The optical data for this study was obtained on Michigan-Dartmouth-MIT's 1.3m telescope located on the southwest ridge at KPNO. The CCL) device used was a Thomson CSF with 0.48 arcsecs per pixel. Rest frame Strömgren *uvby was* obtained using a filter set devised for tbc study color evolution of distant clusters (see Rakes, Schombert and Kreidl 1991). Exposure times ranged from 600 to 900 secs and calibration used standards from Perry, Olsen and Crawford (1 987). Conversion to Johnson *UBV* values was undertaken using the figures from Matsushita (1969). Optical data for M87 was from Persson, Frogel and Aaronson (1979). Optical data for A1795 and A1991 was from McNamara (1991) and Schombert (1987).

The near-IR data for this study were obtained on the KPNO 1.3m using two devices; IRIM, an SBRC 62x58 InSb array plus reimaging optics for a plate scale of 1.35 arcsec pcr pixel and SQIID, a four component camera using separate Hughes 256x256 hybrid platinum silicide arrays. Roth cameras were calibrated using Elias *et* al. (1 982) standards and were corrected for non-linearity using prescriptions found in the NOAO manuals. The IRIM data was taken in a series of ten 60 sec exposures through J (1 .25μm) and K (2.2pm). The SQIID data was taken in series of 180 sec exposures offset to sky every fifth exposure for sky flats. The lower QE on SQIID required much longer tota] exposure times to achieve the same surface brightness depth as IRIM; however, the larger field of view and simultaneous color information reduced the actual overhead. The near-IR data are less deep in surface brightness than the optical data since early-type galaxies arc typically 4 times more luminous at K than at V (5500 Å), but the sky is 10,000 times brighter. Typically the K data was good to 0.1 % of sky which corresponds to 19 K mag arcsec^{-2} or 22 V mag arcsec^{-2}. All the data were corrected for Galactic. extinction and redshift effects using the prescriptions of Thuan and Puschell (1989). Near-IR values for M87 arc from Persson, Frogel and Aaronson (1979).

The optical and near-IR data for cooling flow galaxies arc summarized in 'l'able 1, where *uvy* values have been converted to Johnson *UBV* for comparison to previous studies on cooling flow galaxies. Narrow band data were only taken for normal early-type galaxies and field cooling flow galaxies (see Schombert *et al.* 1993 for a full discussion of this data). Cluster flow data arc either taken from Schombert (1 987) or McNamara (1991). Colors arc quoted as luminosity weighted averages from multi-color surface photometry as described in Schombert *et a/.* (1993). Assuming the mass follows light, then this color represents a mass weighted color. Cosmological parameters of $H_o = 100$ km See 1 Mpc^{-1}, Ω_o = 0.2 and a Virgo distance of 14,5 Mpc arc adopted for this study.

111. Discussion

The near-l]t is the last bandpass sensitive to cool, luminous stellar photospheres and is also the bandpass least effected by extinction from dust and available from the ground. '1'bus, it provides a window into the following 1) stellar mass density, 2) mean Fe/H of the giant population, 3) amount of AGB light, 4) mean age or recent star formation as reflected in the dominance of red supergiants (RSG) and 5) spatial distribution of dust. In contrast, the optical bandpasses (Strömgren *uvby*) used herein arc sensitive to the colors around the 4000Å break, a region for **evolved stellar systems,** such as globulars and early.t,ype galaxies, where subgiants and turnoff dwarfs dominate (Rose 1985). The unique advantage of the Strömgren colors to the study of color evolution in early-type galaxies is outlined in Rakes, Schombert and Kreidl (1991). Briefly, the u — y color is a measure of recent star formation as signaled by blue colors from massive O and B stars, $v - y$ is a metallicity indicator based on the CN blend at 4170Å (see Bell, Hesser and Cannon 1983) and 6 — y is a continuum measure, which for early-type galaxies is a mean color of the composite turnoff main sequence stars and sub-giants. In addition, the $u - v$ color serves as a measure of the 4000Å break. Thus, the baseline between the optical and near-IR allows an investigation into the variations of 1) mean Fe/H, 2) the IMF and 3) recent bursts of SF. These topics were addressed in Schombert *et al.* (1993) for normal early-type galaxies whereas herein we will only discuss the differences between normal and cooling flow galaxies.

The optical colors for both normal early-type galaxies and field cooling flow galaxies arc highly uniform representing only cosmic scatter with no evidence of blue colors, a signature of recent star formation, sharp metallicities changes or exotic stellar populations (e.g. PAGB stars). Although field cooling flows have enjoyed only little interest in optical imaging, they have shown little excess in colors from surveys for distance scale work (see Faber *et* al. 1989) or in specific surveys of x-ray ellipticals (Deustua 1991). On the other hand, some cluster cooling flow galaxies have shown blue color excesses in the optical; however, this was rare and uncorrelated with flow rates. Our three clusters were selected for follow-up near-IR imaging from the sample of McNamara (1 991) because of their unusual optical colors and are not a representative sample of cluster cooling flow "galaxies. The near-IR color, $J - K$, and the cross band color, $V - K$, for all the cooling flow galaxies are also listed in Table 1. The mean colors for field cooling flow galaxies are similar to the mean values from Persson, Frogel and Aaronson (1979) with $< V - K >= 3.36+ 0.03$ and $<3- K>= 0.88+ 0,05$. However, the $V - K$ colors arc clearly deviant when plotted on the $U - V, V - K$ plane shown in Figure 1 ($u - y$ is converted to $U - V$ for comparison to model tracks). Also shown in Figure 1 is an ellipse enclosing 90% of normal early-type galaxies taken from the data of Persson, Frogel and Aaronson (1 979) and Recillas-Cruz *et al. (1* 991). All but one of our normal galaxies (Schombert *et al.* 1993) were located outside this ellipse. In comparison, four of the five field cooling flow galaxies lie outside this ellipse with $V - K$ colors that are 0.2 mags too red in $V - K$ for their $U - V$ colors compared to this sample of normal galaxies, although their $J - K$ colors arc normal for their U — V values.

Color gradients were detected in every color, both optical and near-IR (see Schombert *et al. 1993),* and usually reflects metallicity gradients from the early formation processes where infalling gas is enriched by mass loss from stars (Larson 1975). The mean gradient in the optical were $A(v - y)/\Delta(\log r) = -0.18 \pm 0.08$ which is equivalent to $A(B — R)/\Delta(\log r) = -0.10$ (Schombert *et al.* 1993). The gradients in v – y arc the strongest since it actually measures a metallicity feature (CN at 4170Å). Both normal and cooling flow early-type galaxies displayed similar gradients in v – y and $b - y$. However, in $u - v$, cooling flow galaxies displayed no gradients ($\Delta(u-v)/\Delta(\log r) = 0.00 \pm 0.12$), whereas normal early-type galaxies had a mean gradient of $\Delta(u-v)/\Delta(\log r) = -0.19 \pm 0.09$. The core $u - v$ colors of cooling flow galaxies and normal ellipticals arc the same, but, cooling flow galaxies colors remained red out into their halos rather then the blueward gradients seen in normal galaxies. In non-star-forming stellar systems, red $u - v$ colors signal an enhanced contribution from main sequence stars (higher contribution by objects with higher surface gravity, causing a decreased flux at u relative to v). The same difference is found in the near-lR color gradients. The gradients in $J - K$ arc identical for cooling flow and normal galaxies; however, the gradients in $V - K$ are shallower for cooling flow galaxies (–O. 16 ± ().08) than for normal early-type galaxies (–0.33 ± 0. 10). The core $V - K$ colors arc similar between cooling flow and normal galaxies again indicating, as with the $u - v$ colors, the lack or shallower gradients is due to an increasing contribution from red MS stars at intermediate radii to balance the normal blue metallicity gradient. The $J - K$ and v — y colors arc primarily metallicity driven and, since the $J - K$ and v — y colors and gradients for cooling flow galaxies are similar to same colors for normal galaxies, wc conclude that the differences in u – v and $V - K$ arc I M F related and not a metallicity effect.

The effects of a varying IMF on the optical and near-lli colors of ellipticals was outlined in Aaronson *et al.* (1978) with modifications in Frogel, Persson and Cohen (1980). The diagram of choice for this determination is the $V - K, U - V$ plane shown in Figure 1. The five field cooling flow galaxies with both optical and near-l R colors are shown as solid symbols. They lie from 0.2 to 0.3 mags too red in $V - K$ for their $U — V$ colors which places them close to the $x = 3.0$ line, an IMF with an enriched low main sequence. This enhanced low mass star component is the ideal candidate for the so-called accretion population; however, this AP must have upper mass limits of star formation, M_U, less than 1 $M_\odot$ or the resulting UV emission would be immediately obvious at cooling rates less than 1 % **the** values currently measured (McNamara 1991). If the AP is composed of stars with an IMF $M_U < 1 M_\odot$, then the evolution of this population will not occur within the age of the Universe (i.e.

an increased number of GB stars which would greatly increase the total luminosity of the galaxy). On the other hand, neither can a majority of the galaxy mass be in stars with masses less than 0.5 $M_\odot$, for their contribution to the total luminosity at U, V or K is very small and tbc extreme amount of mass necessary to account for the observed A(V – K) = 0.2 would be very obvious in the internal kinematics of these early-type galaxies (i.e. high M/L's, O'Connell and McNamara 1989). In addition, large numbersofM dwarfs would produce a $J-K$ excess and none is detected; therefore, a majorityof the newly forming tars must be very near the turnoff mass in order to be visible to V–K colors yet missing in $J-K$.

Three of the bluest cluster cooling flow galaxies were selected from the lists of McNamara (1991) for obtaining near-] R images. Shown as open symbols in Figure 1, the cluster cooling flow galaxies have mean optical colors are bluer than normal elliptical by 0.2 to 0.5 mags in $U-V$; however, there is no matching decrease in the near-IR colors as expected by a burst of star formation. For example, star formation with a Galactic IMF produces a $\Delta(B-V)$ = 0.06 after 5 Gyr whereas the near-IR color change is even more dramatic with A(V – K) = 0.60. Aging curves for starbursts of various strengths (defined as b = mass of new stars/mass of galaxy) from the models of Struck-M arcell and Tinsley (1978) are shown in Figure 1 ending at a fiducial point that represents a normal elliptical ($U-V$ = 1.55, $V-K$ = 3.35). The position of cluster cooling flow galaxies in the $V-K$,$U-V$ diagram are inconsistent with a strong burst (b > 0.1), and the data arc only explained by colors indicative of an old ($t \approx 10^9$ yrs), weak (b < 0.001) burst. Given that cluster cooling flows deposit 50 to 100 $M_\odot\,\mathrm{yr}^{-1}$, then a burst strength of less than 0.001 would imply that only 5% of the accreting cooling flow gas is in stars and that 95% of the gas is still present, but not detected by radio observations. If the gas is turned into stars at high efficiency, and the star formation has been constant over the lifetime of the flow, then the expected burst strength is simply the cooling rate over the mass of the galaxy multiplied by some timescale. To have a measurable effect on tbc optical colors, this timescale can be set to the main sequence lifetime of massive stars ($\tau = 10^8$ yrs). This would imply a burst strength of 0.02 which, for an age of τ, occupies a region near $U-V$ = 0.02 and $V-K$ = 2.50, again not seen in the present data. From this wc conclude that, as with field cooling flow galaxies, a majority of the gas in cluster cooling flows is preferentially turned into low *mass* stars with star formation using a truncated IMF. If the underlying AP has a value of A(V – K) = 0.2 as observed in the field galaxies, then a burst strength of between 0.01 and 0,1 is estimated for the cluster cooling flow galaxies, more in alignment with the cooling rates. In addition, as with the field cooling flow galaxies, the cluster cooling flow galaxies studied herein have mean near-IR colors (i.e., $J-K$) that are identical with normal galaxies. '1'bus, there is no indication of a AGB contribution typical of a intermediate age population (a 5% contribution of AGB stars would produce a 0.02 mag difference in $J-K$ colors). In other words, no evidence of a past burst of star formation that produces large numbers of stars in the 4 to 10 $M_\odot$ range is present in the near-IR data for M87, A 1795 or Al 991. in contrast, the cooling flow galaxy NGC 1275, in the Perseus cluster (A426), is undergoing a strong burst in its core and displays an AGB contribution in its near-IR colors ($J - K$ = 1.29, Romanishin 1986). This suggests that, in cluster cooling flow galaxies which arc undergoing weak bursts, these bursts arc very recent (less than 5 Gyr) and very fcw 4 to 10 $M_\odot$ mass stars arc produced (the burst strength for massive stars is less than 0.001).

IV. The nature of star formation in cooling flows

From optical colors it would be concluded that no star formation occurs in field cooling flow ellipticals. Additionally, in cluster cooling flows, when unusual colors are detected, the blue excess is small and one would vastly underestimate tbc efficiency of turning gas into stars leaving a discrepancy between the cooling rates and the amount of cool gas detected. Only observations in the near-IR reveal a hidden accretion population composed of low mass stars. The region in the $V-K$,$U-V$ diagram outlined by field cooling flow galaxies is not attainable with star formation and the narrow band colors rule out metallicity effects. The excess $V-K$ colors for cooling flow galaxies strongly suggests that up to 95% of the accreting gas is placed in low *mass* stars between 1.0 and 0.5 $M_\odot$, primarily in regions outside the core. For cluster cooling flows, a weak burst of short age is indicated, but again with a significant fraction of the star formation in low mass stars. These observations would confirm there exists two different styles of star formation, onc similar to the local IMF, the other skewed towards the production of low mass stars. This difference may be **based** on the mean temperature of the star-forming clouds (Fabian, Nulsen and Canizares 1982, Sarazin and O'Connell 1983). in starburst objects or spiral density waves, the primary method of gas collection and formation of molecular material is shock dissipation. This causes large molecular clouds to form with low temperatures and, therefore, large Jean's lengths advantageous **to the** formation of high mass stars. In cooling flows, the gas is at a higher temperature (due to gravitational beating from infall) and the Jean's length becomes smaller inhibiting the formation of early type stars. Further study of the characteristics of this accretion population would lead to better insight into this two phase star formation theory.

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Figure Captions

Figure 1.- The optical to near-IR two color diagram. Solid lines show models for varying IMF and dashed lines show tracks of constant metallicity. Dash-dot lines show models of starbursts for various strengths ($b =$ mass of new stars/mass of galaxy). The dotted ellipse is the region occupied by normal early-type galaxies taken

from the data of Persson, Frogel and Aaronson (1979) and Recillas-Cruz *et al.* (1991). Field cooling flow galaxies are marked as solid symbols, Cluster cooling flow galaxies are marked as open symbols. Note that the field cooling flow systems lie 0.2 to 0.3 mags too red for their $U-V$ colors indicating an enhanced low mass IMF (x = 3). Cluster cooling flow galaxies display colors indicative of a weak burst of star formation.

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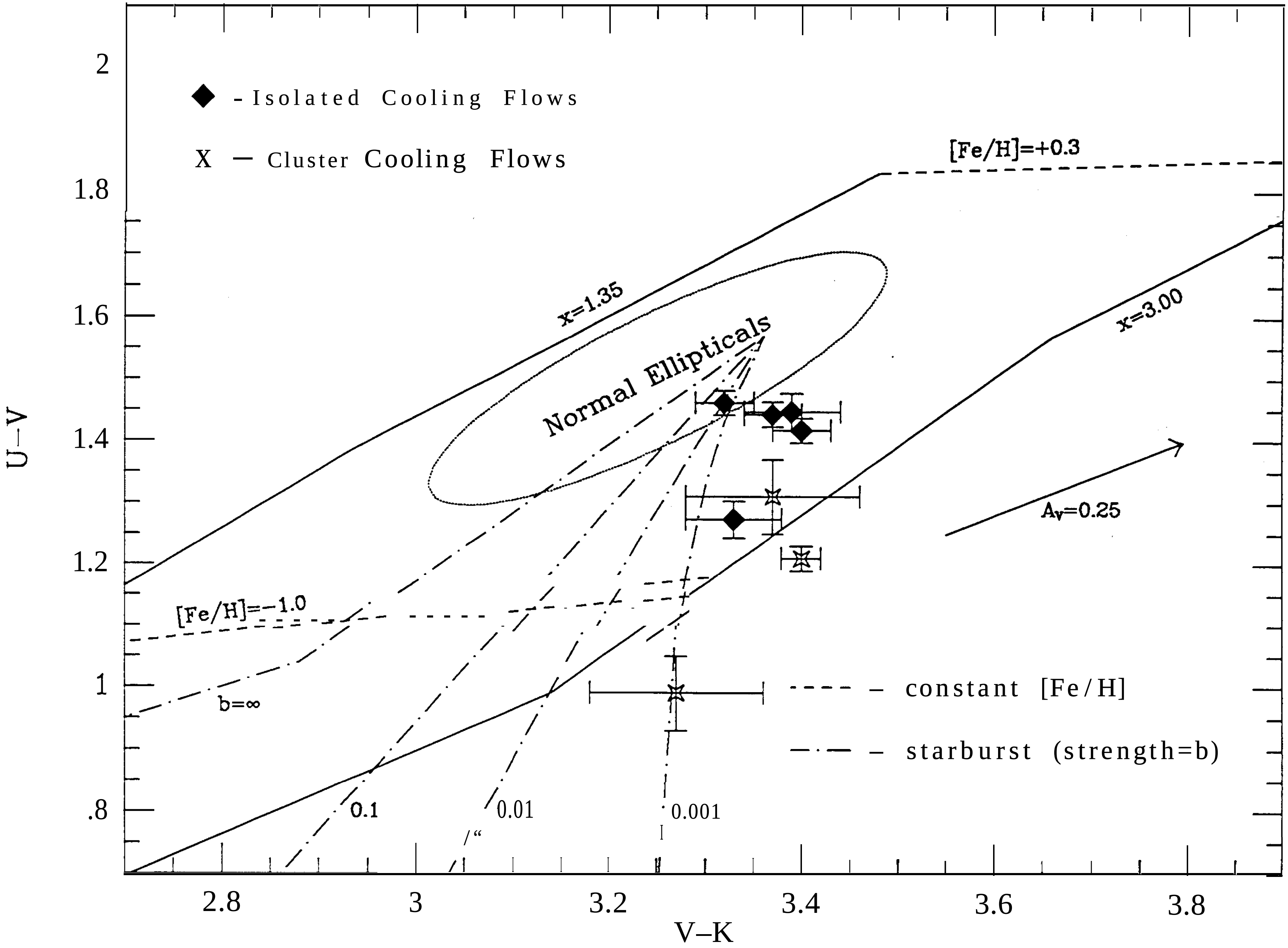
Table 1. Colors for Cooling Flow Galaxies

Galaxy	M_B	$U-V$	$V-K$	$J-K$
NGC 315	−21.6	1.45 ± 0.03	3.39 ± 0.05	0.94 ± 0.05
NGC 2974	−19.2	1.45 ± 0.02	3.40 ± 0.03	0.88 ± 0.03
NGC 4374	−20.4	1.50 ± 0.02	3.32 ± 0.03	0.82 ± 0.03
NGC 4477	−19.0	1.44 ± 0.02	3.37 ± 0.03	0.86 ± 0.03
NGC 7562	−20.1	1.27 ± 0.03	3.33 ± 0.05	0.92 ± 0.05
M87[a]	−21.1	1.21 ± 0,01	3.40 ± 0.02	0.94 ± 0.02
A1795[b]	−22.2	0.99 ± 0.06	3.27 ± 0.09	0.85 ± 0.08
A1991[b]	−22.1	1.31 ± 0.06	3.37 ± 0.09	0.72 ± 0.08

[a] Optical and near-IR values from Persson, Frogel and Aaronson (1979)

[b] Optical values from McNamara (1991)



◆ - Isolated Cooling Flows
X — Cluster Cooling Flows
[Fe/H]=+0.3
x=1.35
x=3.00
Normal Ellipticals
A$_V$=0.25
[Fe/H]=-1.0
b=∞
0.1
0.01
0.001
constant [Fe/H]
starburst (strength=b)
U–V
V–K
2
1.8
1.6
1.4
1.2
1
.8
2.8
3
3.2
3.4
3.6
3.8