THE ASTROPHYSICAL JOURNAL, 416:L61–L65, 1993 October 20

LOW-MASS STAR FORMATION IN COOLING FLOW GALAXIES

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Received 1993 April 23; accepted 1993 July 28

ABSTRACT

Observations are presented based on optical and near-IR imaging to support the idea that isolated 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 ($\dot{M} < 5\ M_{\odot}\ \mathrm{yr}^{-1}$) have normal optical colors and gradients, but red $V-K$ colors signaling an IMF enhanced in low-mass main-sequence stars. Cluster cooling flow ellipticals ($\dot{M} > 50\ M_{\odot}\ \mathrm{yr}^{-1}$) selected to have blue optical colors indicative of recent star formation also show redder $V-K$ colors with respect to expected values for a weak starburst. The strength of the starburst in the $U-V$, $V-K$ diagram indicates an efficiency which places only 5% of the accreting matter into an IMF similar to that found in the Galactic disk and the remaining mass is again sited in low-mass stars.

Subject headings: cooling flows — galaxies: photometry

1. INTRODUCTION

Space observations in the early 1980s demonstrated the presence of massive, hot X-ray halos around field and cluster early-type galaxies (Forman, Jones, & Tucker 1985; Canizares, Fabbiano, & Trinchieri 1987). The X-ray emission arises by thermal bremsstrahlung with average temperatures ranging from 3×10^7 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 are much less than $1/H_0$ producing a flow of accreting gas (Nulsen, Stewart, & Fabian 1984; White et al. 1991).

Detection of H I and CO in cooling flow galaxies confirms the existence of accreting gas (McNamara, Bregman, & O'Connell 1990). However, the amount detected is much smaller than the amount predicted from the cooling rates. One 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 & O'Connell 1989). However, evidence of hot gas is not equivalent to evidence of star formation and the production of an AP. For example, mass loss in bright ellipticals is typically 0.1 to 0.5 $M_{\odot}\ \mathrm{yr}^{-1}$ (Faber & Gallagher 1976) and, combined with a source of UV photons such as post–asymptotic giant branch stars, would produce the kind of Hα emission that has been detected in many ellipticals.

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 exist 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 $M_{\odot}\ \mathrm{yr}^{-1}$ for isolated, field early-type galaxies to over 100 $M_{\odot}\ \mathrm{yr}^{-1}$ for several cluster cooling flows and, averaged over a Hubble time, would imply amounts of cool gas that would produce an AP 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 initial mass function (IMF) similar to the Galactic IMF, then a starburst would occur at a strength that would rival many ultraluminous galaxies. Since an excess of UV and blue light of this magnitude is not 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 are 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. The purpose of this study is to use a narrow blue system of filters (Strömgren *uvby*) to determine the color indices around 4000 Å (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 and dwarfs dominates). If a recent accretion population exists with colors which do not *exactly* mimic an old, giant dominated population, then the baseline from

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3500 Å to 2.2 μm would be the most sensitive to such a detection.

2. OBSERVATIONS AND RESULTS

The optical data for this study was obtained on Michigan-Dartmouth-MIT's 1.3 m telescope located on the southwest ridge at KPNO. The CCD device used was a Thomson CSF with 0".48 per pixel. Rest frame Strömgren *uvby* was obtained using a filter set devised for the study color evolution of distant clusters (see Rakos, Schombert, & Kreidl 1991). Exposure times ranged from 600 to 900 s and calibration used standards from Perry, Olson, & Crawford (1987). Conversion to Johnson *UBV* values, for comparison to stellar population models, was undertaken using the figures from Matsushima (1969). Optical data for M87 were from Persson, Frogel, & Aaronson (1979). Optical data for A1795 and A1991 were from McNamara (1991) and Schombert (1987).

The near-IR data for this study were obtained on the KPNO 1.3 m using two devices; IRIM, an SRBC 62 × 58 InSb array plus reimaging optics for a plate scale of 1".35 per pixel and SQIID, a four component camera using separate Hughes 256 × 256 hybrid platinum silicide arrays. Both cameras were calibrated using Elias et al. (1982) standards and were corrected for nonlinearity using prescriptions found in the NOAO manuals. The IRIM data were taken in a series of 10 60 s exposures through J (1.25 μm) and K (2.2 μm). The SQIID data were taken in series of 180 s exposures offset to sky every fifth exposure for sky flats. The lower QE on SQIID required much longer total 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 are typically 4 times more luminous at K than at V (5500 Å), but the sky is 10,000 times brighter. Typically the K data were good to 0.1% of sky which corresponds to 19 K mag arcsec^{-2} or 22 V mag arsec^{-2}. The sky value was determined by the mean of a series of 15 to 20 sky boxes of 20 by 20 pixels chosen to be outside the halo of the Galaxy or bright stars. All the data were corrected for Galactic extinction and redshift effects using the prescriptions of Thuan & Puschell (1989). Near-IR values for M87 are from Persson, Frogel, & Aaronson (1979).

The optical and near-IR data for cooling flow galaxies are summarized in Table 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 isolated cooling flow galaxies (see Schombert et al. 1993 for a full discussion of this data). Cluster flow data are either taken from Schombert (1987) or McNamara (1991). Mean colors were determined by a luminosity weighting algorithm. This algorithm takes the color along each contour and averages them weighted by the V surface brightness for optical data or the J surface brightness for the near-IR data. This produces an integrated color for the galaxy which represents the mean color as determined by mass (assuming mass follows the light) and independent of contaminating factors from embedded stars or the shape of the galaxy which effect large aperture values. Cosmological parameters of $H_0 = 100$ km s^{-1} Mpc^{-1} $\Omega_0 = 0.2$ and a Virgo distance of 14.5 Mpc are adopted for this study.

TABLE 1

COLORS FOR COOLING FLOW GALAXIES

Galaxy	M_B	log L_x[a]	$U-V$	$V-K$	$J-K$
NGC 315	−21.6	41.31	1.45 ± 0.03	3.39 ± 0.05	0.94 ± 0.05
NGC 2974	−19.2	40.09	1.45 ± 0.02	3.40 ± 0.03	0.88 ± 0.03
NGC 4374	−20.4	40.19	1.50 ± 0.02	3.32 ± 0.03	0.82 ± 0.03
NGC 4477	−19.0	39.43	1.44 ± 0.02	3.37 ± 0.03	0.86 ± 0.03
NGC 7562	−20.1	40.50	1.27 ± 0.03	3.33 ± 0.05	0.92 ± 0.05
M87[b]	−21.1	42.30	1.21 ± 0.01	3.40 ± 0.02	0.94 ± 0.02
A1795[c]	−22.2	44.11	0.99 ± 0.06	3.27 ± 0.09	0.85 ± 0.08
A1991[c]	−22.1	43.33	1.31 ± 0.06	3.37 ± 0.09	0.72 ± 0.08

[a] Isolated galaxies from Canizares et al. 1987; M87 from Fabricant & Gorenstein 1982; A1795 and A1991 from Jones & Forman 1984.

[b] Optical and near-IR values from Persson et al. 1979.

[c] Optical values from McNamara 1991.

3. DISCUSSION

The near-IR 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. Thus, it provides a window into the stellar mass density, mean Fe/H of the giant population, and the mean age or recent star formation as reflected in the dominance of red supergiants (RSG). In contrast, the optical bandpasses used herein (Strömgren *uvby*) are sensitive to the colors around the 4000 Å break, a region for evolved stellar systems, such as globulars and early-type galaxies, where subgiants and turnoff dwarfs dominate (Rose 1985). The advantage of the Strömgren colors to the study of color evolution in early-type galaxies is outlined in Rakos et al. (1991). Each filter is approximately 200 Å wide centered at 3500 Å (*u*), 4100 Å (*v*), 4750 Å (*b*), and 5500 Å (*y*). Briefly, the $u - v$ color serves as a measure of the 400 Å break, $v - y$ is a metallicity indicator based on the CN blend at 4170 Å (see Bell, Hesser, & Cannon 1983) and $b - y$ is a continuum measure, which for early-type galaxies is a mean color of the composite turnoff main-sequence stars and subgiants, 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 colors 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.

Our sample, described in full in Schombert et al. (1993), consists of 18 normal early-type galaxies and five isolated galaxies with high X-ray luminosities (isolated in the sense that they are not associated with known cluster X-ray sources). In addition, three cluster cooling flows were selected for further near-IR study from the sample of McNamera (1991) because of their unusual blue optical colors (note that these are *not* representative sample of cluster cooling flow galaxies as a whole in that most have normal, red optical colors). The X-ray luminosities of the isolated cooling flow galaxies are listed in Table 1 and mass deposit rates vary from 0.5 to 3 $M_\odot$ per year. The cluster cooling flow objects, also in Table 1, are distinguished by total X-ray luminosities that are a factor of 1000 higher and mass deposited rates from 50 to 200 $M_\odot$ per year.

The optical colors for both normal early-type galaxies and isolated cooling flow galaxies are highly uniform representing only cosmic scatter with no evidence of blue colors, a signature of recent star formation. Although isolated cooling flows have not been studied as a class in the optical, they have shown little excess in colors or emission lines from surveys for distance scale work (see Faber et al. 1989) or in specific surveys of X-ray

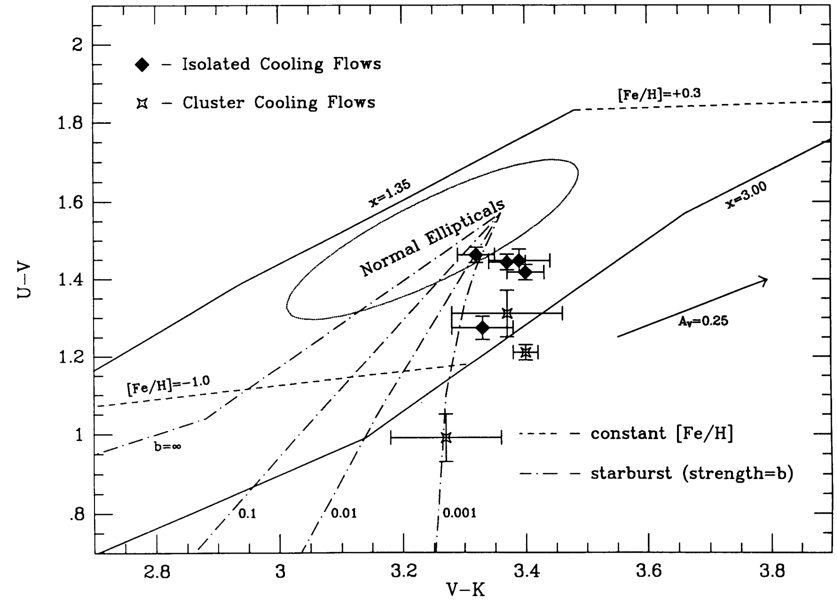

FIG. 1.—Optical to near-IR two color diagram. Solid lines show models for varying IMF and dashed lines show tracks of constant metallicity. Dash-dot lines show models of starbursts for various strengths (b = mass of new stars/mass of Galaxy). The dotted ellipse is the region occupied by normal early-type galaxies taken from the data of Persson et al. (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 isolated 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.

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 (O'Connell & McNamara 1989). The near-IR color, $J-K$, and the cross-band color, $V-K$, for all the cooling flow galaxies are listed in Table 1. The mean colors for our normal galaxies are similar to the mean values from Persson et al. (1979) with $U-V = 1.50 \pm 0.10$, $V-K = 3.24 \pm 0.13$ and $J-K = 0.87 \pm 0.04$. However, the isolated X-ray galaxy colors are 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). In Figure 1, an ellipse enclosing 90% of normal early-type galaxies taken from the data of Persson et al. (1979) and Recillas-Cruz et al. (1991) is drawn. The slope of this elliptical shaped region reflects the color-magnitude relation, an effect of greater mean metallicity for a galaxy of higher mass. All but one of our normal galaxies were located inside this ellipse. In contrast, four of the five isolated cooling flow galaxies lie outside this ellipse, and all the cluster galaxies lie outside this region (although this was expected since the cluster galaxies were selected for their unusual colors).

This deviation for isolated X-ray galaxies is primarily in $V-K$ since the color-magnitude relation correctly predicts the $U-V$ colors from their absolute magnitudes. For example, the average absolute magnitude is -20.1 for the isolated X-ray galaxies in Table 1 which corresponds to 1.47 in $U-V$ (Schombert et al. 1993; Griersmith 1982), similar to the observed values. However, the predicted $V-K$ colors for the same absolute luminosity is 3.27, which underestimates the observed values by 0.1 to 0.2 mags. Thus, the $V-K$ colors for the galaxies with high X-ray luminosities are 0.15 mags too red in $V-K$ for their $U-V$ colors compared to this sample of normal galaxies. On the other hand, the $J-K$ colors for the isolated cooling flow galaxies (0.88) are normal for the $U-V$ values.

Another difference was detected in the color gradients for isolated cooling flow galaxies and the normal galaxy sample. 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). Both normal and isolated X-ray galaxies displayed similar gradients in $v-y$ and $b-y$, with the gradients being the strongest in $v-y$ since it measures an actual metallicity feature (CN at 4170 Å). However in $u-v$, the 4000 Å break color, isolated X-ray 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 isolated X-ray galaxies and normal ellipticals are the same, so where normal galaxies have blue gradients reflecting decreasing metallicity with radius we deduce that isolated X-ray galaxies have redder than normal halos. We note that in non–star-forming, old stellar systems, red $u-v$ colors usually signal an enhanced contribution from lower main-sequence stars (higher contribution by objects with higher surface gravity, causing a decreased flux at u relative to v).

The same effect is found in the near-IR color gradients. The gradients in $J-K$ are identical for isolated X-rays and normal galaxies; however, the gradients in $V-K$ are slightly shallower for isolated X-ray galaxies (-0.20 ± 0.10) than for normal galaxies (-0.34 ± 0.12). The core $V-K$ colors are similar between isolated X-ray and normal galaxies again indicating, as with the $u-v$ colors, that an increasing contribution from red MS stars at intermediate radii to balance the normal blue metallicity gradient is present. The $J-K$ and $v-y$ colors are primarily metallicity driven and only weakly dependent on IMF effects (Aaronson et al. 1978). On the other hand, $u-v$ and $V-K$ are more sensitive to IMF effects. Since the $J-K$ and $v-y$ colors and gradients for isolated X-ray galaxies are identical to normal galaxies, we conclude that the differences in $u-v$ and $V-K$ are IMF related and not a metallicity effect.

The effects of a varying IMF on the optical and near-IR colors of ellipticals was outlined in Aaronson et al. (1978) with the modifications in Frogel, Persson, & Cohen (1980). The diagram of choice for this determination is the $V-K$, $U-V$ plane shown in Figure 1. The five isolated cooling flow galaxies with both optical and near-IR colors (*solid symbols*) lie 0.1 to 0.2 mags too red in $V-K$ for their $U-V$ colors. This places them close to the $x = 3.0$ line, where x is the slope of the IMF given by $\phi(m) \propto m^{-(1+x)}$ for 13 Gyr population. A larger value of x represents a stellar population with an IMF enriched in low main-sequence stars. 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 and blue 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., a larger 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 the extreme amount of combined stellar mass necessary to account for the observed $\Delta(V-K) = 0.2$ would be very obvious in the internal kinematics of these early-type galaxies (i.e., high M/L's, O'Connell & McNamara 1989). In addition, large numbers of M dwarfs would produce a $J-K$ excess and none is detected. Therefore, if the $V-K$ excess is due to low-mass stars, a majority of the newly forming stars must be very near the turnoff mass between 0.5 and 1.5 $M_\odot$.

As stated above, the three cluster cooling flow galaxies were selected from the lists of McNamara (1991) for obtaining near-IR images due to their unusual blue colors. Shown as open symbols in Figure 1, the cluster cooling flow galaxies have mean optical colors are bluer than a typical brightest cluster member ($M_B = -22$, Schombert 1987) by 0.3 to 0.6 mags in $U-V$. However, also note from Figure 1, 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 $\Delta(V-K) = -0.60$. Aging curves for starbursts of various strengths (defined as b = mass of new stars/mass of Galaxy) from the models of Struck-Marcell & Tinsley (1978) are shown in Figure 1 ending at a fiducial point that represents a bright elliptical ($M_B = -22$, $U-V = 1.55$, $V-K = 3.35$). 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 are only explained by colors indicative of an old ($t \approx 10^9$ yr), weak ($b < 0.001$) burst. Given that cluster cooling flows deposit 50 to 100 $M_\odot$ 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 the optical colors, this timescale can be set to the main-sequence lifetime of massive stars ($\tau = 10^8$ yr). 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. Thus, the behavior for cluster cooling flows from previous optical studies and seen in optical two color diagrams, that the amount of star formation is much less than predicted by the mass deposit rates, is confirmed without optical to near-IR colors.

Since there still exists a discrepancy between the flow rates and the burst strengths in the $U-V$, $V-K$ diagram, it is possible that the IMF for cluster cooling flows is also truncated as proposed above for the isolated X-ray galaxies. If the underlying AP has a value of $\Delta(V-K) = 0.2$ as observed in the isolated 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 isolated 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. Thus, there is no indication of an asymptotic giant branch (AGB) contribution typical of an intermediate age population (a 5% contribution of AGB stars would produce a 0.02 mag difference in $J-K$ colors). In other words, there is no evidence of a past burst of star formation that produces large numbers of stars in the 4 to 10 $M_\odot$ range in the near-IR data for M87, A1795 or A1991. 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 are undergoing weak bursts, these bursts are very recent (less than 5 Gyr) and very few 4 to 10 $M_\odot$ mass stars are produced (the burst strength for massive stars is less than 0.001) in agreement with our scenario of enhanced low-mass star formation.

4. THE NATURE OF STAR FORMATION IN COOLING FLOWS

From optical colors it would be concluded that no star formation occurs in isolated cooling flow ellipticals. Additionally, in cluster cooling flows with unusual blue colors, the blue excess is small and one would vastly underestimate the efficiency of turning gas into stars leaving a discrepancy between the cooling rates and the amount of cool gas detected. Our observations in the near-IR suggest a hidden accretion population composed of low-mass stars. The region in the $V-K$, $U-V$ diagram outlined by isolated cooling flow galaxies is not attainable with star formation and the narrow-band colors imply that metallicity effects are not responsible for the observed differences. The excess $V-K$ colors for isolated X-ray 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, to reconcile the mass deposit rates with the burst strengths, a significant fraction of the star formation must be low-mass stars producing a near-IR excess. These observations would suggest there exist two different styles of star formation, one similar to the local IMF, the other skewed toward the production of low-mass stars. This difference may have its origin in the mean temperature of the star-forming clouds (Fabian, Nulsen, & Canizares 1982; Sarazin & 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 Jeans lengths advantageous to the formation of high-mass stars. In cooling flows, the gas is at a higher temperature (due to gravitational heating from infall) and the Jeans lengths 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 possible two-phase star-formation theory.

The authors wish to acknowledge the generous allocation and support of the telescopes at MDM and KPNO. The research described in this *Letter* was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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