STAR FORMATION IN COOLING FLOWS

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ABSTRACT. Star formation, probably with an abnormal initial mass function, represents the most plausible sink for the large amounts of material being accreted by cD galaxies from cooling flows. There are three prominent cases (NGC 1275, PKS 0745-191, and Abell 1795) where cooling flows have apparently induced unusual stellar populations. Recent studies show that about 50% of other accreting cD's have significant ultraviolet excesses. It therefore appears that detectable accretion populations are frequently associated with cooling flows. The questions of the form of the IMF, the fraction of the flow forming stars, and the lifetime of the flow remain open.

1. INTRODUCTION: THE FATE OF GAS IN CLUSTER COOLING FLOWS

This is less a review than a prospectus for a process which, if it occurs, may play a fundamental role in the evolution of cD galaxies and perhaps many other ellipticals. The process is the conversion of material in cooling flows accreted by galaxies into stars--"accretion populations". The difficulty confronting this idea is that observational evidence has been scanty and contradictory. Recent studies, however, lend more credence to it and indicate that accretion populations may be a widespread phenomenon.

The X-ray evidence for cooling flows in clusters of galaxies has been thoroughly reviewed recently by Fabian, Nulsen, & Canizares (1984) and Sarazin (1986a), and I will not recover that ground. Estimated accretion rates, $\dot{M}$, range from $\sim 10\ M_{\odot}\ yr^{-1}$ for modest nearby cases such as M87, where sensitivity is good, to $500\text{-}1000\ M_{\odot}\ yr^{-1}$ for extreme cases like Abell 1126 and PKS 0745-191. The age of the flows cannot be accurately estimated, but since the cooling time in their centers is less than the Hubble time it is possible that they have continued for $t_{CF} \sim 10$ Gyr. At a typical accretion rate of $\dot{M} \sim 100\ M_{\odot}\ yr^{-1}$, $\sim 10^{12}\ M_{\odot}$ would then have been deposited, which is comparable to the stellar mass of a typical cD galaxy. (To avoid any dispute over nomenclature, I will use "cD" in this paper to designate the "centrally dominant" galaxy which is observed to be located in the center of cluster cooling

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flows.) Accretion from cooling flows could clearly have dramatic consequences for the evolution of cD galaxies.

There are not many viable repositories for this massive inflow (cf. Fabian et al. 1982, Sarazin & O'Connell 1983, White & Sarazin 1986). Accretion onto a compact massive object would generate extraordinary nonthermal activity at levels of 100 $M_\odot$ yr^{-1} and would also lead to excessive central velocity dispersions, which are not observed (e.g. Malumuth & Kirshner 1985). Limits on cool interstellar material in nearer accretors are orders of magnitude below the values implied by the accretion rates (e.g. Burns et al. 1981, Valentijn & Giovanelli 1982). This appears to leave star formation as the only plausible sink for accreted material.

Star formation with the initial mass function (IMF) prevailing in our Galaxy would be easily detectable at typical accretion rates, as shown by the following simple estimate. The fraction of the V light contributed by an accretion population is given by $f_v = (\dot{M}t_{CF})/[(M/L_v)_{AP} L_{tot}]$, where $(M/L_v)_{AP}$ is the visual mass-to-light ratio of the accretion population and L_{tot} is the V luminosity of the underlying galaxy (all values will be expressed in solar units). Typical accreting cD's have integrated $M_v = -23.5$ ($H_o = 50$), implying $L_{tot} = 2.1 \times 10^{11}$. Larson & Tinsley (1978) give convenient estimates for the mass-to-light ratios of populations with continuous, uniform star formation. (They employ an IMF, truncated at a lower limit of 0.1 $M_\odot$, which is slightly different from the best current estimate [Scalo 1986] for normal Galactic star formation but is certainly close enough for our purposes.) For a 10 Gyr-old population, they find $M/L_v = 2.0$. Such a population will have a broad-band (U-V) color -1.2 mag bluer than a normal gE galaxy and a (λ2500 - V) color -3.8 mag bluer than normal. For an accretion rate of 1 $M_\odot$ yr^{-1}, the accretion population would produce 2.4% of the integrated V light and UV excesses which would be only marginally detectable with current instrumentation. However, a rate of only 5 $M_\odot$ yr^{-1} would yield 12% of the V light and unambiguous excesses of -0.25 in (U-V) and -1.72 in (λ2500 - V). (These are integrated average values; localized measures--e.g. of the nucleus--could, of course, yield smaller values if little material were deposited there.) It turns out that because $(M/L_V)_{AP}$ declines quickly with t_{CF}, and colors become rapidly bluer, these excesses are only weakly dependent on the assumed t_{CF}, changing less than a factor of 2 for lifetimes between 10 Gyr and 0.1 Gyr.

Given the fact (see Sec. 2) that color anomalies in most accretors are small, the upper limit to the amount of mass being converted into stars with a normal IMF in typical accreting cD's is of order 5 $M_\odot$ yr^{-1}, independent of the lifetime of the cooling flow. This is only a small fraction of the typical accretion rate and a minuscule 1% of the more extreme rates. It is evident that if accretion populations are to be repositories for typical cooling flows, we require $(M/L_v)_{AP} >> 2$. This has led to the proposal that star formation in cooling flows is preferentially weighted toward low mass stars and hence large mass-to-light ratios (Cowie & Binney 1977, Fabian et al. 1982, Sarazin & O'Connell 1983; see also Jura 1977). There are several theoretical reasons for expecting shifts of the IMF to lower masses, including the lower density of dust in the flows, higher shear, and, most importantly, the lower Jeans mass which is a consequence of the high gas pressure in the flows. None of these arguments are rigorous, however.

Sarazin & O'Connell (1983, hereafter SO) calculated colors for 10 Gyr-old accretion populations with power-law IMF's characterized by the index x (in the notation of Larson & Tinsley 1978), an upper mass limit M_U and a lower mass limit M_L. With $M_L = 0.1$, models with $M_U = 0.75$ or 1.0 yield $(M/L_V)_{AP}$ in the range 3-50 for x ~ 0-2, high enough to accommodate typical flows without large disturbances to optical and infrared colors. An interesting possibility to explore in the future is a bimodal IMF (Larson 1986) with a suppressed high mass mode.

Cooling flows, at much smaller rates, probably also exist in many normal elliptical galaxies not associated with cluster cores (Nulsen et al. 1984; Forman et al. 1985; Sarazin 1986b; Fabian, this conference). Arguments concerning the fate of material in these flows are similar to those above. Here, however, because many of the putative accretors are bright, nearby objects, more stringent limits on star formation with a normal IMF may be placed, perhaps as small as $SRF/L_V = 10^{-12}\ M_\odot\ yr^{-1}\ L_\odot^{-1}$ (O'Connell 1986). I will not discuss these cases further here.

Of course, a fundamental alternative to the accretion population interpretation is that the $\dot{M}$'s in cooling flows have been badly overestimated. Rates are estimated from quantities readily determined from the X-ray data ($\dot{M} \sim L_X/T$ in the absence of heating, where the values refer to the region inside the cooling radius). There is much independent X-ray evidence that cooling flows exist (cf. Sarazin 1986a), and further very strong support comes from the correlation between optical line emission and cooling times for cluster gas (Hu et al. 1985). However, there is ongoing debate over the importance of various heating mechanisms such as conduction (Bertschinger & Meiksin 1986), supernovae explosions (Silk et al. 1986), and galaxy motions (Miller 1986), among others. I leave this controversy to others, except to remark that plausible reductions in $\dot{M}$ from such processes may not be very large (e.g. supernova heating by a normal IMF reduces $\dot{M}$ by only a factor of 2, Silk et al. 1986).

2. OBSERVATIONAL EVIDENCE FOR ACCRETION POPULATIONS

Analyses of three reasonably solid detections of accretion populations have been published. The best studied, and perhaps most remarkable, case is that of NGC 1275 in the Perseus cluster (Abell 426) for which $\dot{M} \sim 300\ M_\odot\ yr^{-1}$. SO suggested that the unusual A-star absorption line spectrum and optical colors of NGC 1275 were consistent with an accretion population with $M_U \sim 3\ M_\odot$ and $x \sim 1.5$ if M_L were lowered to 0.001 $M_\odot$. Later (V-K) measures are consistent with this model (Romanishin 1986). Independent evidence for an absence of high mass stars comes from vacuum ultraviolet (Fabian, Nulsen & Arnaud 1984) and infrared (Gear et al. 1985) observations. Population synthesis of an optical spectrum by Wirth et al. (1983) finds no evidence for early B or O stars, and the contribution of the earliest type present (B5, 5 $M_{\odot}$) is probably overestimated because of contamination by the nuclear nonthermal source. While these studies all agree on the absence of massive stars in NGC 1275, this could be produced by a decrease in the star formation rate over the last few 10^7 yrs rather than a truncation of the IMF. Whatever M_U, however, the bulk of the 300 $M_{\odot}$ yr^{-1} being accreted must be going into objects of much lower mean mass than for a normal IMF.

Another spectacular accretor is PKS 0745-191 (Fabian et al. 1985), where the estimated accretion rate is ~1000 $M_{\odot}$ yr^{-1}. In this instance, optical data are not very good yet, but the spectrum shows strong emission lines and a very blue continuum, with evidence of a color gradient. Formation of stars well above 1 $M_{\odot}$ is evidently vigorous.

The third case is less dramatic than the two preceding. IUE and optical band spectrophotometry of NGC 6166, the accreting cD in Abell 2199, shows evidence of a small (~4% of the V light) young population (Bertola et al. 1986). In this case, the IUE spectrum clearly indicates the presence of O stars. In fact, a far UV upturn suggests the IMF is more abundant in O stars than is normal, though this could be caused instead by a recent surge in the star formation rate. As expected from the figures quoted in Sec. 1, Bertola et al. derive a total star formation rate for NGC 6166 of only a few $M_{\odot}$ yr^{-1} if the IMF is normal, which is to be compared to an estimated accretion rate of 110 $M_{\odot}$ yr^{-1} (Sarazin 1986a). In a case like NGC 6166, where only modest spectral anomalies are present, it would be important to distinguish the effects of a putative accretion population from those of the old, hot star population apparently responsible for the far-UV light in normal E's. It is not obvious that this can be done unambiguously yet (cf. Burstein et al. 1986), but Bertola et al. (1986) argue that anomalies at optical wavelengths support their young star interpretation.

As for the other known accreting cD's, published studies indicate they are outwardly normal in the optical region. This is actually a rather soft statement, since they are typically faint objects which have not received careful study. Various investigators have obtained broad band colors or spectra for nuclear velocity dispersion studies but not necessarily with the precision necessary to detect small departures in energy distribution or in the 3400-4500 A region where the largest effects might be expected. Romanishin (1986) made (V-K) observations to search for accretion population effects in 8 cases and, apart from NGC 1275, found no peculiarities. However, for M_U slightly below 1 $M_{\odot}$, the SO models have the interesting property that accretion populations hardly disturb the infrared energy distribution, so this is not necessarily a serious difficulty. Romanishin and Hu et al. (1985) found no evidence to support Valentijn's (1983) claim of unusual (B-V) color gradients in accretors, which apparently resulted from a slight miscalibration in his surface photometry.

Romanishin also compiled previously published U-V and g-r photometry on accretors, mostly taken with apertures over 20" in diameter. Known accretors again did not separate from non-accretors. However, there are puzzling inconsistencies here. Two of the objects with normal claimed g-r colors are NGC 6166 and Abell 1795. While the anomalies in the former (as described above) are confined to shorter wavelengths and might not be reflected in g-r colors, A1795 has manifestly unusual colors (see below). A number of other accretors have UV excesses which have not been previously reported (see below). It therefore appears that earlier studies may not constitute a suitable database for investigation of accretion population effects.

3. NEW SPECTROSCOPIC STUDIES

Two recent studies designed especially to search for such effects in the 3400-5000 A spectra of cD's with cooling flows indicate that accretion populations are frequently present. First, from IPCS measurements with the AAT of the 4000 A break and Hβ emission line strengths in 9 accretors, Johnstone et al. (1986) argue that a small fraction (0.1% to 10%) of the cooling flow forms into stars with a normal IMF which then help to maintain the ionization of the extended emission line filaments. They suggest that the bulk of the inflow is deposited into faint, low mass objects.

The other study (O'Connell et al. 1986, hereafter OSWM) is based on KPNO 4-m IIDS observations with a 5" diameter entrance aperture. Flux-calibrated spectrophotometry with 12 A resolution was obtained of 9 accretors and of a control sample of other cD's known not to have large cooling flows, which serve as templates of normal spectra. Template objects were chosen such that color differences with the accretor sample caused by luminosity or aperture effects should be minimized. The spectra were corrected for foreground reddening and registered by a cross-correlation technique. Ratio spectra were generated by dividing the accretor spectra by the template. Examples are shown in Figures 1 and 2, where the template is the sum of the two non-accreting cD galaxies MKW 1 and MKW 2. A color excess, δUV, between the galaxies and the template is based on the magnitude difference in 100 A bands centered at 3600 A and 4500 A. It is insensitive to emission lines, and excesses larger than about 0.05 mag are significant.

Five of the nine accretors in the sample exhibit significant δUV's: M87, A1795, A1991, A2052, and NGC 6166. All but A1795 have δUV ~ -0.2 to -0.3; the excess for NGC 6166 is apparently consistent with the data of Bertola et al. (1986). A1795, with δUV = -0.54 and an AF-type absorption spectrum, is a clearcut case of an accretion population (see Figure 1). A spectrum centered 10" (17.5 kpc) south of the nucleus is similar in appearance, with δUV = -0.33. The color anomaly is therefore unrelated to nuclear nonthermal activity. Johnstone et al. (1986) confirm this result. The unusually blue (B-V) of A1795 is also apparent in the spectra of Hu et al. (1985), though they do not comment on it.

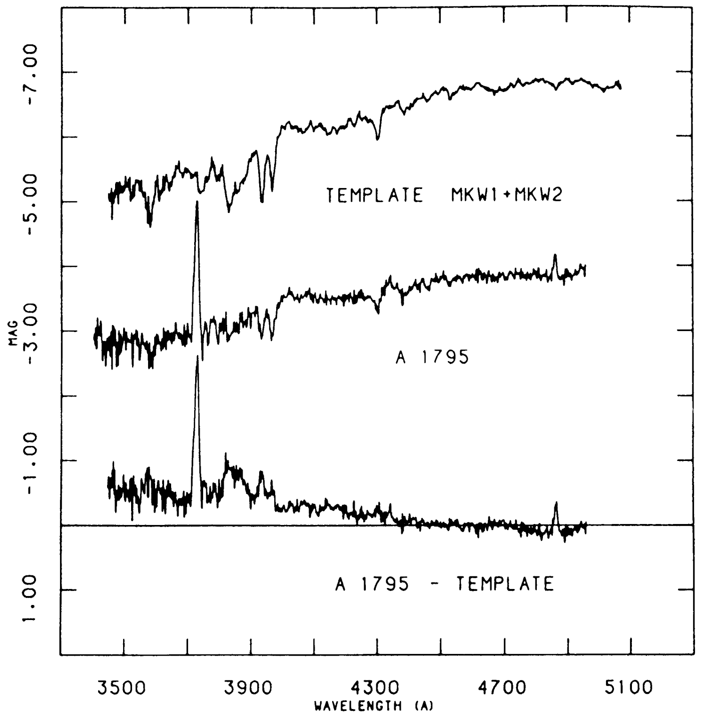

Figure 1: Middle panel: An unsmoothed spectrum (2 A per channel) of the accreting cD galaxy Abell 1795 in the restframe with arbitrary normalization, expressed in magnitudes. Upper panel: The mean spectrum of the non-accreting cD's MKW 1 and MKW 2, as for A1795. Lower panel: The ratio of the A1795 spectrum to the upper panel template, expressed in magnitudes and normalized at 4500 A. The large UV excess and weak stellar absorption features in the ratio spectrum are evidence of an accretion population. Strong emission lines of [O II] and hydrogen are also present.

The absence of significant color gradients in their data is further evidence of the unimportance of nuclear optical non-thermal radiation.

M87 is also worth comment. In this case, the template is the sum of the nuclear spectra (5" aperture) of the two Virgo E's NGC 4374 and 4552. As mentioned by de Vaucouleurs earlier in this conference, the nucleus of M87 exhibits a definite ultraviolet excess with respect to the template (δUV = -0.29) and strong, broadened emission lines. The stronger absorption lines show evidence of filling by a weak-lined continuum, which could be either a hot accretion population or non-thermal radiation. The UV excess is also present, though smaller (-0.10 to -0.20), at positions 10" and 20" north of the nucleus. This seems larger than would be produced by the normal decrease of metallicity with radius (cf. the U-R broad-band photometry of Davis et al. 1985), but without further analysis the issue cannot be decided.

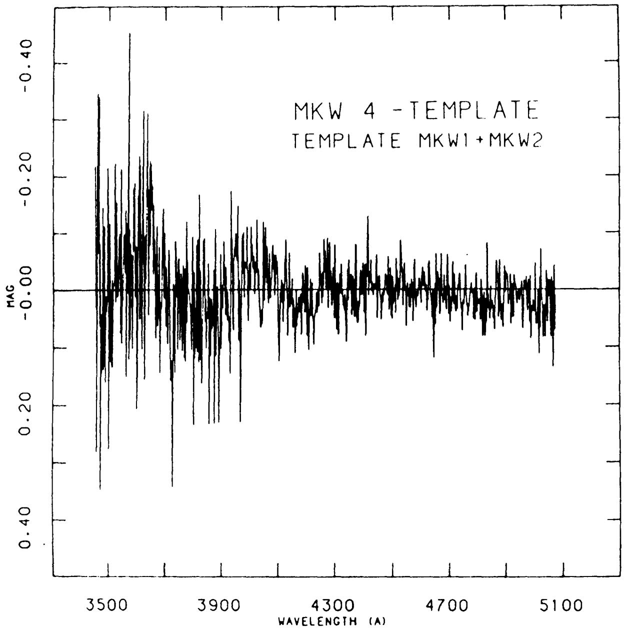

FIGURE 2: The ratio of the spectrum of the accreting cD MKW 4 to the MKW 1 + MKW 2 non-accretor template, as in Fig. 1 but with an enlarged vertical scale. Unlike A1795, there is no significant evidence for emission lines or unusual stellar populations in MKW 4.

Population synthesis of the objects in the OSWM sample is under way in an attempt to separate hot star effects from those of non-thermal radiation, internal dust, or metallicity. Our preliminary analysis suggests that accretion population models of the type described by SO, with $M_L = 0.1\ M_\odot$ and $M_U \sim 1$-$2\ M_\odot$ for $x \sim 1$-2, are compatible with the observed nuclear spectra for all the UV-excess objects except A1795. A fully consistent "conservative" accretion population interpretation such as this would also demand, however, that similar δUV values be observed at larger radii. (Note that absorption lines would be weakened by the fact that accreting gas appears to have sub-solar abundances [Sarazin 1986a] as well as by the contribution of stars hotter than normal for a gE.) Owing to the uncertain precision of the published photometry (see Sec. 2), it is unclear whether this is the case. Should further work not confirm an extended area of UV-excess, then the estimated $\dot{M}$'s would require that $M_L << 0.1\ M_\odot$ and/or $x > 2$. The data for A1795 already require such values (as in the case of NGC 1275, see Sec 2).

The other four accretors in the OSWM sample (AWM 4, MKW 3s, MKW 4, and A2029) do not exhibit significant UV excesses or other spectral anomalies (see Figure 2), apart from weak line emission in MKW 3s. The size of δUV in the OSWM sample is not correlated with the estimated global $\dot{M}$ nor with $\dot{M}/M_{stars}$ (derived assuming that the normal stellar

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population has constant M/L_V), which should be a good index of the expected effect of accretion on the integrated spectrum. In fact, two of the apparent non-detections (A2029 and MKW 3s) have larger values for these quantities than any of the detections except A1795.

The only positive correlation emerging from this relatively small sample is that all objects with significant δUV's have strong nuclear emission lines. Hu et al. (1985) have shown that such emission is found only in objects with cluster gas cooling times less than 7 $h^{-1/2}$ Gyr. However, there are many objects with short cooling times and little evidence of either optical emission lines or population anomalies. Abell 2029, an object which would "seem to be an ideal candidate for observing cooling flows" (Cowie et al. 1983) on the basis of X-ray evidence, is perhaps the best example.

4. SUMMARY AND CONCLUSION

There are three unambiguous cases (NGC 1275, PKS 0745-191, and Abell 1795) of unusual stellar populations apparently induced by cluster cooling flows. Approximately 50% of other accreting cD's in a relatively small sample exhibit nuclear ultraviolet excesses probably indicating accretion populations. The presence of UV excesses and other spectral anomalies is correlated with the presence of strong nuclear line emission but not with estimated global $\dot{M}$ or $\dot{M}/M_{stars}$.

Star formation with a normal (Galactic) initial mass function and the estimated $\dot{M}$'s would produce much larger color anomalies than observed in typical accretors. In most cases, less than 1-10% of the estimated $\dot{M}$ can be deposited in this form. This constraint is not substantially altered if one assumes that the cooling flow has a lifetime much shorter than a Hubble time.

Accretion population models with roughly normal values of M_L and x but lowered M_U's can possibly explain a minority of cases. But the optical properties of most accretors apparently demand that most of the estimated $\dot{M}$ is deposited in an "invisible", very low mass form (M_L << 0.1 $M_\odot$ and/or x > 2). In the case of IMF's with lowered M_U's, a reduced cooling flow lifetime does significantly relieve the observational constraints and permits less extreme parameters to be assigned.

The situation cannot be said to be satisfactory. Perhaps the least unpalatable of the various available alternatives is that the $\dot{M}$'s have been correctly estimated and that star formation with an abnormal IMF is the respository for the accreted material but that typical cooling flows have persisted for only a fraction of a Hubble time. The strong evolution of X-ray structure with redshift which that interpretation would require should be readily susceptible to test with AXAF.

REFERENCES

Bertola, F., Gregg, M.D., Gunn, J.E., & Oemler, A. 1986, Ap.J., **303**, 624.

Bertschinger, E., & Meiksin, A. 1986, Ap.J. (Letters), **306**, L1.

Burns, J.O., White, R.A., & Haynes, M.P. 1981, A.J., **86**, 1120.

Burstein, D., Bertola, F., Faber, S.M., & Lauer, T. 1986, in preparation.

Cowie, L.L., & Binney, J. 1977, Ap.J., **215**, 723.

Cowie, L.L., Hu, E.M., Jenkins, E.B., & York, D.G. 1983, Ap.J., **272**, 29.

Davis, L.E., Cawson, M., Davies, R.L., & Illingworth, G. 1985, A.J., **90**, 169.

Fabian, A.C., Arnaud, K.A., Nulsen, P.E.J., Watson, M.G., Stewart, G.C., McHardy, I., Smith, A., Cook, B., Elvis, M., & Mushotzky, R.F. 1985, M.N.R.A.S., **216**, 923.

Fabian, A.C., Nulsen, P.E.J., & Arnaud, K.A. 1984, M.N.R.A.S., **208**, 179.

Fabian, A.C., Nulsen, P.E.J., & Canizares, C.R. 1982, M.N.R.A.S., **201**, 933.

----- 1984. Nature, **310**, 733.

Forman, W., Jones, C., & Tucker, W. 1985. Ap.J., **293**, 102.

Gear, W.K., Gee, G., Robson, E.I., & Nolt, I.G. 1985. M.N.R.A.S., **217**, 281.

Hu, E.M., Cowie, L.L., & Wang, Z. 1985. Ap.J. Suppl., **59**, 447.

Johnstone, R.M., Fabian, A.C., & Nulsen, P.E.J. 1986, preprint.

Jura, M. 1977, Ap.J., **212**, 634.

Larson, R.B. 1986. M.N.R.A.S., **218**, 409.

Larson, R.B., & Tinsley, B.M. 1978, Ap.J., **219**, 46.

Malumuth, E.M., & Kirshner, R.P. 1985, Ap.J., **291**, 8.

Miller, L. 1986. M.N.R.A.S., **220**, 713.

Nulsen, P.E.J., Stewart, G.C., & Fabian, A.C. 1984. M.N.R.A.S., **208**, 185.

O'Connell, R.W. 1986. In Proc. of the STScI Conference on Stellar Populations, eds. C. Norman, M. Tosi, & A. Renzini (Cambridge: Cambridge Univ. Press), in press.

O'Connell, R.W., Sarazin, C.L., White, R.E., & McNamara, B. 1986. In preparation.

Romanishin, W. 1986. Ap.J., **301**, 675.

Sarazin, C.L. 1986a, Rev. Mod. Phys., **58**, 1.

----- 1986b. In Proc. Green Bank Workshop on Gaseous Haloes Around Galaxies, eds. J. Bregman & F. Lockman, in press.

Sarazin, C.L. & O'Connell, R.W. 1983, Ap.J., **268**, 552.

Scalo, J.M. 1986. In IAU Symposium No. 116, "Luminous Stars and Associations in Galaxies", eds C.W.H. de Loore, A.J. Willis & P. Laskarides, (Reidel, Dordrecht), p. 451.

Silk, J., Djorgovski, S., Wyse, R.F.G., & Bruzual, A.G. 1986, preprint.

Valentijn, E.A. 1983. Astr. Ap., **118**, 123.

Valentijn, E.A., & Giovanelli, R. 1982, Astr. Ap., **114**, 208.

White, R.E., & Sarazin, C.L. 1986, Ap.J. Supp., in press.

Wirth, A., Kenyon, S.J., & Hunter, D.A. 1983, Ap.J., **269**, 102.

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DISCUSSION

Richstone: If cooling flows make heavy haloes, wouldn't cD's be completely at rest in cluster centers?

Sarazin: No. Gravitational interactions with other cluster galaxies will always give cD's velocities greater than 100 km/s.

White: I have two questions. First, could you or Andy Fabian comment on recent work by Bertschinger and Meiksin which claims that mass deposition rates drop by an order of magnitude when conductive effects are included? Second, what is known about the metallicity of the X-ray gas in elliptical cooling flows? If E's have "no" supernovae resulting from the star formation processes responsible for the bulk of the observed stars, where do the heavy elements come from?

Fabian: Large temperature gradients are observed in the hot gas so conduction is a possibility. However, the Bertschinger and Meiksin calculations, which reduce our inferred values for M by a factor of $\sim$ 10, do not appear to account for the low temperature ($10^7 K$) gas seen in X-ray lines by the Einstein Observatory SSS and FPCS. The emission measure of this gas is just what is expected from cooling.

O'Connell: My theoretical colleagues inform me they have two objections to the claims that conduction can realistically reduce estimated accretion rates. First, that conduction can be readily suppressed by tangled magnetic fields. And second, that only over a narrow range of conductive efficiency would you find both that conduction is important *and* the increased central densities apparently resulting from some degree of cooling in the gas. Efficient conduction would result in an isothermal halo. It seems unlikely that conduction can operate at just the right level in all the cluster X-ray sources which show some evidence of cooling, since these have a very wide range of physical characteristics. A final observational point is that you may need a factor of 100 reduction in the estimated flow rates to make the optical observations consistent with star formation with a normal IMF in some accretors.
Concerning metal abundances, the visible stars in most accretors appear to be normal E galaxy populations, presumably formed long ago with a normal IMF. The intracluster gas was evidently enriched in metals by such populations at an early stage of cluster evolution, ejected, and now is raining back onto the galaxies in the form of cooling flows. The abundances in the intracluster gas are about 1/2 of solar, so that stars forming from cooling flows will be a factor 2-10 times less metal rich than typical E galaxy stars. You are certainly right that if the IMF for accretion populations is truncated below the threshold mass for supernovae, no further enrichment will occur. I don't know what the situation is with regard to abundances of X-ray gas in normal E's.

Canizares: There is no information about abundances from the X-ray data for any ellipticals other than those at the centers of rich clusters.

Schechter: We've heard a lot about conservation of mass but little about conservation of angular momentum. Is there reason to think these systems won't form disks?

O'Connell: Not really. Cluster gas wil tend to have small but not, of course, zero angular momentum. Disklike structures might well form; but as conditions in the flow change, their orientation could change. Cowie, Hu and collaborators find the emission line filaments to be organized in thick disks. It would be very interesting to study the spatial distribution of color in systems with detected accretion populations in order to look for disklike structures.

N. Bahcall: Very large accretion rates of $10^{2-3} M_\odot$/yr that create low mass stars are likely to cause considerable deviations from the standard parameter correlations of elliptical galaxies, such as those observed between velocity dispersion, surface brightness, and effective radius (including the Faber-Jackson relation). Since the above relations for ellipticals are rather tight, those galaxies expected to have large accretion rates should deviate in a unique manner from the standard curves. Has this been checked, and, if so, what does it show?

O'Connell: Mass-to-light ratios have been looked at by Romanishin using data from Malumuth and Kirshner; he found no obvious effects. Non-accreting cD's have nuclear $M/L_v \sim 10$ but show a fairly large scatter. A typical accretion flow lasting for 10 Gyr would not push M/L_v beyond that scatter. Most M/L determinations are based on nuclear velocity dispersion measurements, which may not reflect the full effects of the accretion population if it is deposited preferentially at large radii. Dressler (1981, *Astrophys. J.*, **243**, 26) found an increasing velocity dispersion with radius in Abell 2029, which has a large cooling flow, and that could be regarded as evidence for an accretion population in its outer parts.

Kochhar: What does the gas do in the cases which do not show a UV excess?

O'Connell: Assuming that the mass accretion rates are correct, we presume that it forms into stars with a mean mass well below $1 M_\odot$, which will not have a significant effect on the optical energy distribution. For an upper mass cutoff around 0.7 $M_\odot$, the Sarazin and O'Connell models show that even infrared colors will be insensitive to the accretion population.

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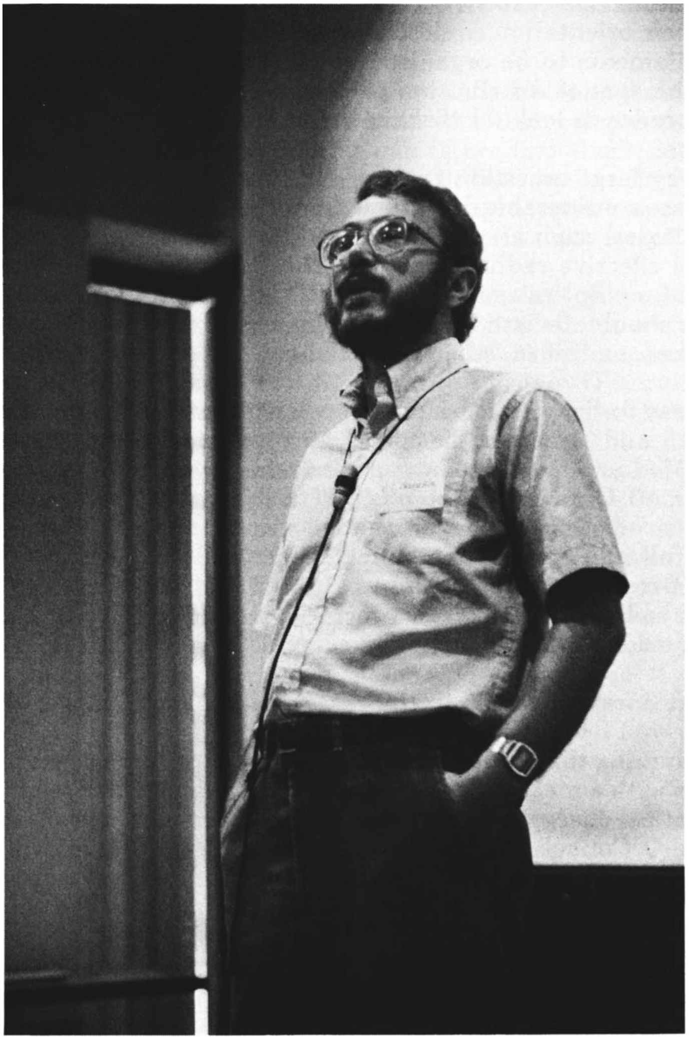

Craig Sarazin.