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SELF-IRRADIATED COOLING CONDENSATIONS: THE SOURCE OF THE OPTICAL LINE EMISSION FROM COOLING FLOWS

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ABSTRACT

The optical filaments seen at the centers of clusters of galaxies, which cannot be explained by standard photoionization or shock models, can be straightforwardly interpreted as self-irradiated cooling condensations. Fully developed ($\sim 10^4$ K) condensations embedded in thermally unstable 10^7 K gas will be bathed in a powerful EUV/soft X-ray flux emanating from the surrounding condensing regions. Our models of the condensation/irradiation process give line ratios and luminosities similar to those observed. Because we assume that the condensations arise from linear perturbations, which grow significantly only when the local cooling time is less than the free-fall time, condensing regions of the type modeled here should arise only in cooling flows of central pressure $\gtrsim 10^{-9}$ ergs cm^{-3} and should extend only over the inner regions of the cluster.

Subject headings: galaxies: clustering — galaxies: intergalactic medium — galaxies: X-rays — X-rays: general

I. INTRODUCTION

In this *Letter*, we present a model to explain the filamentary optical line emission seen at the centers of clusters of galaxies (Heckman 1981; Cowie *et al.* 1983; Hu, Cowie, and Wang 1985) and which have proved difficult to interpret in terms of the usual photoionization and shock models (Heckman *et al.* 1989, hereafter HBvM). In many clusters of galaxies, the observed X-ray emissivities, surface brightnesses, and temperatures indicate the presence of a hot ($\sim 5 \times 10^7$ K), extensive (> 300 kpc) intracluster medium (see Sarazin 1988). Often, the cooling time in this medium is less than a Hubble time, suggesting that matter must sink toward the center of the cluster in a "cooling flow" (Cowie and Binney 1977; Fabian and Nulsen 1977). Observations of X-ray emission lines, characteristic of 10^{6-7} K intracluster gas, bolster the cooling flow hypothesis (see Canizares, Markert, and Donahue 1988). As this gas cools further, perhaps en route to forming stars, it should pass through an optical-line emitting phase. However, the available thermal energy in 10^4–10^5 K gas is far too low to account for the strength of the optical emission.

If one computes the mass accretion rates, $\dot{M}$, of cooling flows from Hα line emission by assuming that each H atom in the flow recombines 1–3 times (Cowie *et al.* 1983), the resulting accretion rates exceed the inflow rates derived from the X-ray data ($\dot{M}_X$) by factors of 10–100 (HBvM). Furthermore, if $\dot{M}$ increases with r, as suggested by the X-ray data (see Thomas, Fabian, and Nulsen 1987), the problem worsens because the Hα emission is generally confined to the central 10 kpc (HBvM), while the core radius of the X-ray surface brightness typically ranges from 300 to 500 kpc. Nevertheless, the Hα emission does appear to be related to the mass inflow rate, since HBvM found that the Hα luminosity is correlated with $\dot{M}$ at a 99.9% confidence level.

The optical forbidden lines present a further challenge: [O II] λ3727 and [N II] λ6583 can be stronger than Hα by factors of 3 and 2, respectively (HBvM; McNamara and O'Connell 1989). Also prominent in cooling flow spectra are [S II] λ6716, 6731, [O I] λ6300, and [O III] λ5007. The distribution of the [N II]/Hα ratios in these objects is distinctly bimodal, suggesting that they should be divided into two classes: one with [N II]/Hα ≈ 2.0 (HBvM class I), and one with [N II]/Hα ≈ 0.9 (HBvM class II). Although photoionization by an AGN power-law continuum produces [N II]/Hα ratios similar to those observed in class II objects, neither AGN photoionization models nor shock models adequately explain the observed line ratios in class I objects (HBvM). Photoionization by hot-star continua also fails to fit these ratios (see HBvM).

The line-emitting gas can extend over tens of kiloparsecs, as in NGC 1275, but is usually brightest over the central few kiloparsecs, where the gas pressures of the filaments, inferred from the [S II] line ratio, are 1–2 $\times 10^{-9}$ ergs cm^{-3} (HBvM). Presumably, these filaments are pressure-confined by hotter (10^7 K) gas, which, in the absence of a heating source, will cool radiatively. As the hot gas cools through 10^6 K and condenses, it will emit EUV and soft X-ray radiation which can photoionize the previously condensed filaments and fuel an optical emission-line spectrum. We will show that this picture self-consistently explains the observed spectra and luminosities of the filaments.

We present our model in two parts. Section II illustrates how cooling condensations develop at the high pressures of the central filamentation region, and § III describes a photoionization model for the irradiated filaments, which we use to compute emission-line ratios and luminosities. In § IV we briefly discuss our results.

II. THE DEVELOPMENT OF COOLING CONDENSATIONS

In the absence of a stabilizing heat source, the hot gas at the centers of clusters of galaxies will cool radiatively and condense into cooler, denser clouds on a time scale t_c (Fabian and Nulsen 1977; Mathews and Bregman 1978). Gas of pressure $P = P_9 \times (10^{-9}$ ergs cm^{-3}), temperature $T = T_7 \times (10^7$ K), and cooling function $\Lambda = \Lambda_{23} \times (10^{-23}$ ergs cm^3 s^{-1}) cools in a time $t_c \sim (6 \times 10^6 \text{ yr}) T_7^2 P_9^{-1} \Lambda_{23}^{-1}$, where we have integrated over temperature assuming $\Lambda \propto T^{-1/2}$, appropriate for

$10^5 < T < 2 \times 10^7$ K (Raymond, Cox, and Smith 1976). If this gas extends over a region of radius $r_c = r_1 \times (1\ \mathrm{kpc})$ at the center of a cluster, it will condense at a rate $\dot{M} \sim (8\ M_\odot\ \mathrm{yr}^{-1})\ P_9^2 T_7^{-3} \Lambda_{23} r_1^3$, releasing a luminosity $L_c \approx 5kT\dot{M}/2\bar{m} \sim (2 \times 10^{42}\ \mathrm{ergs\ s}^{-1}) P_9^2 T_7^{-2} \Lambda_{23} r_1^3$, where $\bar{m}$ is the mean mass per particle.

The size of the high-pressure region will be limited by the velocity at which the surrounding hot gas can flow in and replenish it, giving $r_{\max} \sim t_c(5kT/3\bar{m})^{1/2} \sim (3\ \mathrm{kpc}) T_7^{5/2} P_9^{-1} \Lambda_{32}^{-1}$. Thus, pressures of order $P_9 \sim 1$ can persist only over the central few kpc. In NGC 1275, where the radial variations of the [S II] line ratio have been observed, the expected trend holds: $P_9 \approx 2$ at a projected radial distance of 0.5 kpc, $P_9 \approx 1$ at a projected radius of 1 kpc, and $P_9 \approx 0.5$ at projected radius of 2 kpc (HBvM). For a central region in which $r_c \approx r_{\max}$, the maximum possible mass flow and luminosity are $\dot{M}_{\max} \sim (220\ M_\odot\ \mathrm{yr}^{-1}) P_9^{-1} T_7^{9/2} \Lambda_{23}^{-2}$ and $L_{c,\max} \sim (5 \times 10^{43}\ \mathrm{ergs\ s}^{-1})\ P_9^{-1} T_7^{11/2} \Lambda_{23}^{-2}$.

As the hot gas cools and condenses, the fastest growing condensation modes will have a wavelength of order the sound speed times the cooling time (Field 1965; McCray, Stein, and Kafatos 1975) and will collapse isobarically with a characteristic column density $N_{\rm char} \sim (7 \times 10^{21}\ \mathrm{cm}^{-2}) T_7^{3/2} \Lambda_{23}^{-1}$. Shorter-wavelength modes will be conductively suppressed; longer-wavelength modes will first collapse isochorically, then temporarily develop repressurizing shocks before relaxing to subsonic accretion (David, Bregman, and Seab 1988). Because $N_{\rm char}$ drops with T, the cooling condensations will fragment hierarchically into smaller and smaller bits. At 10^5 K, $N_{\rm char}$ reaches a minimum value $N_{\min} \sim 10^{17}\ \mathrm{cm}^{-2}$ before the precipitous drop in the cooling function halts the fragmentation. At 10^4 K, radiative heating due to the surrounding gas will reestablish thermal equilibrium (see § III), and the fragments can begin to accrete gas subsonically.

These small, cool cloudlets will quickly achieve a high covering factor relative to the high-pressure region. If the cooling gas condenses into cloudlets of thickness $N_{\min}$, the total surface area of cloudlets will become of order $4\pi r_c^2$ in a time $\sim t_c(N_{\min} kT/Pr_c) \ll t_c$. As gas continues to flow into the central region and condense, the total column density of cool matter will grow until self-gravitation induces the clouds to coalesce and collapse. If the velocity dispersion of the cloudlets is similar to the temperature of the gas in which they are embedded, self-gravitation will begin to dominate the cloudlet dynamics at a total column density $N_{\rm cr} \sim (P/\pi G \bar{m}^2)^{1/2} \sim (7 \times 10^{22}\ \mathrm{cm}^{-2}) P_9^{1/2}$, regardless of the temperature of the intercloud gas. Such a column density of cool gas, which can accumulate in a time $\sim t_c(N_{\rm cr} kT/Pr_c) \sim (2 \times 10^8\ \mathrm{yr}) P_9^{-3/2} T_7^3 \Lambda_{23}^{-1} r_1^{-1}$, will absorb photons up to several keV in energy, assuming its metallicity is near solar. Thus, the cool cloudlets, if they are fairly uniformly distributed about the high-pressure region, can absorb much of the luminosity released by the cooling hot gas and reprocess it into an emission-line spectrum of similar luminosity.

III. A PHOTOIONIZATION MODEL FOR COOLING CONDENSATIONS

Small 10^4 K cloudlets embedded in a larger region of 10^{5-7} K cooling gas will be bathed in an ionizing EUV/soft X-ray flux and will reradiate this incident energy in hydrogen recombination lines and optical forbidden lines. The details of the emergent spectrum depend primarily upon two factors: the total incident energy flux and the spectral shape of that flux. Our photoionization models for these cloudlets give spectra which reproduce remarkably well the line ratios observed in the optical filaments at the centers of clusters of galaxies.

In the preceding section, we showed that 10^4 K condensations of column density $\gtrsim 10^{17}\ \mathrm{cm}^{-2}$ will pervade the central region, quite possibly with a total column density sufficient to capture the bulk of the EUV/X-ray luminosity produced there. If cloud-cloud shielding is ignored, the energy flux, F_E, incident upon these cloudlets will be $\sim L_c/4\pi r_c^2 \sim (2 \times 10^{-2}\ \mathrm{ergs\ cm}^{-2}\ \mathrm{s}^{-1}) P_9^2 T_7^{-1} r_1$. Including cloud-cloud shielding would reduce the overall flux by attenuating the low-energy portion of the spectrum; however, we do not attempt to model these effects here.

The spectral shape, $f(\nu)$, of the incident ionizing radiation will be that of an ionized plasma cooling from $T_{\rm hi} = T_7(10^7\ \mathrm{K})$ to $T_{\rm lo} = 10^4$ K. Hence, the expression

$$f(\nu) = \int_{T_{\rm lo}}^{T_{\rm hi}} \frac{\Lambda_\nu(T)}{\Lambda(T)}\, dT\ , \tag{1}$$

where $\Lambda_\nu(T)$ is the spectrally resolved cooling function and $\Lambda(T)$ is the total cooling function, gives $f(\nu)$ with unit normalization. Once again, in the interest of maintaining simplicity, we neglect the effects of cloud-cloud shielding, which will tend to harden the spectral shape.

We compute the function $f(\nu)$ using the latest version of the Raymond-Smith optically thin plasma emission code (Raymond, Cox, and Smith 1976; Raymond and Smith 1977), which assumes that the emitting plasma is in coronal equilibrium. Although the assumption of coronal ionization equilibrium is not likely to be valid below a temperature of about $10^{6.4}$ K (Gaetz and Salpeter 1983), this is not a serious problem for two reasons. First, because the luminosity of the cooling gas at a given temperature is proportional to T, the majority of the ionizing spectrum is determined by the gas hotter than $10^{6.4}$ K. Second, even though gas at cooler temperatures will be more highly ionized than it would be in coronal equilibrium, it will still cool via emission of spectral lines in a similar band of the EUV spectrum. Nevertheless, an accurate treatment of the non-ionizing C IV, N V, and O VI line emission from these flows will require a nonequilibrium calculation.

Using the photoionization code CLOUDY (Ferland 1989), we have calculated the optical emission-line spectra induced by ionizing fluxes of magnitude $F_E \sim 0.1\ \mathrm{ergs\ cm}^{-2}\ \mathrm{s}^{-1}$ and shape $f(\nu)$ incident upon a 10^4 K cloudlet of pressure $P_9 \approx 1$ for various values of $T_{\rm hi}$ and cloudlet column density. The results of our runs for $T_{\rm hi} = 10^7$ K and cloudlet column density of $10^{18}\ \mathrm{cm}^{-2}$ are presented in Table 1. Abell 2052, the cluster to which we compare our line ratios in Table 1, is an HBvM class I cluster, chosen because it has been observed in [O II] and [O III] (McNamara and O'Connell 1989), as well as in the Hα to [S III] region by HBvM. The agreement between the observed line ratios and those we predict is remarkably good, considering the simplicity of our model. We will present more complete results of these photoionization models in a forthcoming paper (Donahue and Voit 1990).

In calculating $f(\nu)$ we have ignored the radiation that can be produced by the repressurizing shocks which form in long-wavelength condensations (see David, Bregman, and Seab 1988). However, these shocks achieve velocities of at most 120 km s^{-1} and therefore contribute less than $\sim(10^{-3}\ \mathrm{ergs\ cm}^{-2}\ \mathrm{s}^{-1}) P_9 T_7^{-1}$ to the total ionizing flux incident on a cloudlet, $<10\%$ of that generated by the cooling gas. This seems paradoxical at first, since the emission-line spectra induced by these

TABLE 1

OPTICAL EMISSION-LINE FLUXES RELATIVE TO Hβ[a]

	F_E[b]		
EMISSION LINE	0.087	0.174	A2052
Hα	2.70	2.70	2.7[c]
N II λ6584	4.08	4.20	4.8[c]
S II λ6717	1.65	1.19	1.5[c]
O III λ5007	0.46	1.90	0.84[d]
O II λ3726+λ3729	11.57	13.66	8.13[d]
O I λ6300	0.70	0.42	0.7[c]

[a] For $P_9 \approx 1$, $T_{\rm hi} = 10^7$ K, and cloudlet thickness of 10^{18} cm^{-2}.

[b] In units of ergs cm^{-2} s^{-1}.

[c] HBvM, normalized so that Hα/Hβ = 2.7.

[d] McNamara and O'Connell 1989.

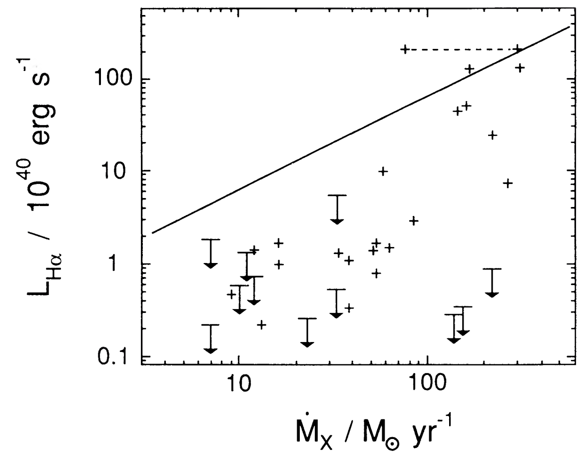

FIG. 1.—Hα luminosity as a function of $\dot M_X$ in cooling flows. The solid line in this figure shows the maximum $L_{\rm H\alpha}$ that can be generated by a given $\dot M$, assuming all the cooling radiation emerging from gas cooler than $T_{\rm hi} = 10^7$ K is transformed into Hα radiation with an efficiency of 3%. The cooling flow data have been taken from Table 9 of HBvM. (Values of $\dot M_X$ are reliable only to a factor $\sim$2.) Virtually all cooling flows lie near or to the lower right of this line, indicating that the observed $\dot M_X$ is sufficient to power the optical filaments via the self-irradiation mechanism. In many instances, the central $L_{\rm H\alpha}$ indicates that only a fraction of $\dot M_X$ reaches the filamentation region. Only NGC 1275 lies well above the maximum value, at the point on the left of the dotted line. However, adopting $\dot M_X \approx 300\ M_\odot$ yr^{-1}, as suggested by White and Sarazin (1988), gives the point on the right of the dotted line, also consistent with this model.

shocks exhibit higher ionization than the spectra modeled here. But, because these shocks emit only lower energy UV photons, which do not penetrate as deeply as the EUV/soft X-ray photons coming from the cooling gas, they produce comparatively thin ionized regions. The radiation from the cooling gas, deposited over a much thicker region, gives a lower ionization state but higher line luminosities.

Our models indicate that $\sim$3% of the energy absorbed by a filament will emerge in the Hα line, so an ensemble of cloudlets of total column density greater than a few times 10^{22} cm^{-2} will reprocess the EUV/soft X-ray cooling radiation into Hα with an efficiency $\sim$3%. If the column density of the ensemble is much smaller than this, the efficiency of transformation into Hα drops by a factor of only a few. Even a single, isolated cloud of column density 10^{18} cm^{-2} will reemit an Hα flux $\sim$0.5% of the incident flux. Given that $L_{c,\max} \sim (5 \times 10^{43}$ ergs s$^{-1})P_9^{-1}T_7^{11/2}\Lambda_{23}^{-2}$ (see § II), we thus obtain a corresponding $L_{\rm H\alpha,max} \sim (1.5 \times 10^{42}$ ergs s^{-1}) $P_9^{-1}T_7^{11/2}\Lambda_{23}^{-2}$. For comparison, $L_{\rm H\alpha} \approx 2.1 \times 10^{42}$ ergs s^{-1} in NGC 1275.

In Figure 1 we compare the observed Hα luminosities of cooling flows to their X-ray–derived mass accretion rates ($\dot M_X$). We display all the clusters listed in Table 9 of HBvM with an observed $\dot M_X$, excluding 3C 295 and Cygnus A in which the filaments are likely to be photoionized by an AGN (HBvM). The solid line gives the expected $L_{\rm H\alpha}$ if all the cooling radiation coming from gas below 10^7 K in a flow of magnitude $\dot M_X$ were converted into Hα radiation at the maximum efficiency of 3%, i.e., $L_{\rm H\alpha} = 0.03[5k(10^7\ {\rm K})\dot M_X/2\bar m]$. In all of these objects except NGC 1275, reprocessing of the cooling radiation can account for the observed Hα emission. And, if we adopt $\dot M \approx 300\ M_\odot$ yr^{-1} for NGC 1275, as suggested by White and Sarazin (1988), then the $L_{\rm H\alpha}$ from this object is also consistent with our model. Abell 2052, with $\dot M_X \approx 54\ M_\odot$ yr^{-1}, is a more typical cluster; its Hα luminosity ($L_{\rm H\alpha} \approx 1.7 \times 10^{40}$ ergs s^{-1}) is only 5% of the maximum value allowed when $T_{\rm hi} = 10^7$ K.

IV. DISCUSSION

The line-emitting nebulosity observed at the centers of clusters of galaxies appears to arise naturally from the condensations expected to form in a cooling flow. Soft X-ray and UV radiation from cooling 10^{6-7} K gas irradiates the cooler (10^4 K) clouds that pervade the condensing region and fuels a powerful emission-line spectrum that closely matches the spectra of the filaments observed in some clusters. The mass flows necessary to produce the observed Hα luminosities are less than or equal to those implied by the X-ray emission, characteristically being lower by a factor $\sim$10. Taken as a whole, this model provides a powerful confirmation of the presence of cooling flows in clusters of galaxies and suggests that the $\dot M$ at the centers of many of these flows is only moderate compared to that derived from X-ray observations at larger radii.

X-ray surface brightness deconvolutions also indicate that, in many clusters, $\dot M$ decreases with decreasing radius (Thomas, Fabian, and Nulsen 1987; White and Sarazin 1988), so it seems odd that the line-emitting nebulosity, which appears to be a signature of condensing gas, should be so centrally concentrated. However, buoyancy effects may drastically alter the development of condensations at high r (Loewenstein 1989; Balbus and Soker 1989). Convective motions will suppress thermal instability in linear perturbations when the free-fall time $t_{\rm ff}$ ($\sim r/v_*$ at radius r, where v_* is the stellar velocity dispersion of the central galaxy) is smaller than t_c. Our model, in which the growth of linear perturbations engenders finely grained inhomogeneity and self-irradiation, therefore applies only when

$$P \gtrsim v_* \frac{(kT)^2}{r\Lambda} \sim (2 \times 10^{-10}\ {\rm ergs\ cm^{-3}}) \times \left(\frac{v_*}{300\ {\rm km\ s^{-1}}}\right)\left(\frac{r}{10\ {\rm kpc}}\right)^{-1} T_7^2 \Lambda_{23}^{-1}\ , \quad (2)$$

i.e., when the flow has attained a near-sonic velocity ($\gtrsim v_*$). Because $PT^{-2}r$ decreases with radius (see Fabian, Nulsen, and Canizares (1984), condensing regions of the kind described here will arise in only the inner regions of cooling flows with sufficiently high central pressure.

Perhaps the initially nonlinear perturbations thought to collapse and decouple from cooling flows at large r (Nulsen 1986; Balbus and Soker 1989) condense homogeneously or with a low aggregate covering factor, making them much less efficient at reprocessing cooling radiation. Clumpier flows would then have a lower central $\dot{M}$ as well as lower $L_{H\alpha}$. Observations of cooling condensations at larger radii but lower pressure would help significantly to complete this picture.

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