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CALCIUM DEPLETION IN COOLING-FLOW NEBULAE AND THE ORIGIN OF THE LINE-EMITTING GAS

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ABSTRACT

We present upper limits on the [Ca II] λ7291 flux from emission-line nebulae in cluster cooling flows. The observed lack of [Ca II] emission indicates that gas-phase calcium is underabundant in cooling-flow nebulae and is most likely depleted onto dust grains. If calcium in the line-emitting filaments is largely bound into dust, then these filaments probably did not condense out of the hot intracluster gas.

Subject headings: cooling flows — dust, extinction — galaxies: clusters: individual (2A 0335+096, A496, Hydra A, S1101) — galaxies: ISM

1. INTRODUCTION

Both X-ray imaging and X-ray spectra suggest that the hot gas at the centers of many clusters cools and condenses in less than a Hubble time, removing the central pressure support and thus initiating a "cooling flow" in which gas settles slowly inward through the cluster core (Fabian, Nulsen, & Canizares 1984, 1991). When cooling flows were first proposed, it seemed natural that this cooling gas would eventually be visible at optical wavelengths. Unusual emission-line nebulae, characterized by extremely luminous Balmer and low-ionization forbidden-line emission, are indeed often associated with the central galaxies in cluster cooling flows (Heckman 1981; Cowie et al. 1983; Hu, Cowie, & Wang 1985; Johnstone, Fabian, Nulsen 1987; Heckman et al. 1989; see Baum 1992 for a recent review). The spectra of cooling-flow nebulae feature prominent [O II], [N II], and [S II] lines, demonstrating that the nebular gas has been enriched in metals and is clearly not primordial. Early theoretical work (Mathews & Bregman 1978; Cowie, Fabian, & Nulsen 1980) posited that this line emission came from repressurizing shocks associated with condensation of gas out of the intracluster medium (ICM), but the luminosities of cooling-flow nebulae, which reach 10^{42} ergs s^{-1} in Hα alone, turned out to be up to several hundred times larger than those generated by simple cooling (Johnstone, Fabian, & Nulsen 1987), far too large to be produced by repressurizing shocks (David, Bregman, & Seab 1988).

Current explanations for the high emission-line luminosities require the filaments to be "energized" somehow, presumably by either photoionization or shocks. The high [N II] λ6584/Hα ratios, ranging from ~ 1 to $\gtrsim 2$, require a large amount of heating per ionization and support models in which the filaments are photoionized by an ionizing spectrum rich in 50–100 eV photons. Voit & Donahue (1990) and Donahue & Voit (1991) have calculated the line emission expected when condensed gas within a cooling flow is photoionized by soft X-ray and EUV radiation from surrounding gas that is still condensing. Our models satisfactorily reproduce the puzzling line ratios of cooling-flow nebulae and exemplify a class of models in which photoionizing radiation from cooling of hot gas supplies the power. Other such models include turbulent mixing layers (Begelman & Fabian 1990; Crawford & Fabian 1992; Slavin, Shull, & Begelman 1993) and high-velocity shocks (Binette, Dopita, & Tuohy 1985). Schemes like these, in which ionizing photons transfer energy from hot gas to the emission-line nebulae, predict that if the filaments are dust-free, as would be expected of gas that had cooled from X-ray emitting temperatures, then they ought to emit copiously in the [Ca II] λλ7291,7325 lines, at fluxes up to $\frac{1}{3}$ of the Hα line flux.

In this *Letter*, we present data showing that cooling-flow filaments are not strong [Ca II] emission-line sources. We argue that, barring unexpected dust resiliency in the extremely hot environment of the ICM, this lack of [Ca II] emission indicates the filaments may be dusty, and therefore do not come directly from the hot intracluster medium. This is not the first indication that the central galaxies of clusters might contain dusty gas, but it is the only evidence for dust that requires the line-emitting filaments *themselves* to be dusty.

2. OBSERVATIONS

This search for [Ca II] emission from cooling-flow filaments is part of a larger spectroscopic survey of a complete sample of clusters of galaxies (Donahue 1993). As part of this survey, we obtained medium-resolution red spectra of the emission-line nebulae at the centers of four cooling flows in 1992 December at the Las Campanas 100″ (2.5 m) duPont telescope. We used the Modular Spectrograph with a CRAF CCD and an 85 mm camera equipped with a 1200 l mm^{-1} grating blazed at 7500 Å and a 2″ slit. Our wavelength range of 1200 Å allowed us to observe [N II] λ6584, Hα, and [Ca II] λ7291 simultaneously. Table 1 summarizes these observations.

The spectra, centered on $\sim$7100 Å, depending on the object redshift, were dispersed at 1.18 Å $pixel^{-1}$, giving a resolution of 3.0 Å. The frames were reduced in a standard way with IRAF. A constant bias was subtracted from all frames, and a bias-subtracted image composed of the median of 15 zero-length exposures was subtracted from all object frames and flats to remove two-dimensional variations in bias level. Pixel-to-pixel variations were removed with dome flats that had been fitted and normalized to conserve counts along the spectrum. Illumination corrections along the slit were found to be insignificant. The object frames were dispersion-corrected with arc lamp exposures of a hollow cathode and neon source. A fit good to $\sim$0.12 Å (rms) was achieved with 30–31 features spanning the wavelength coverage. S-distortion was removed by fitting the traces of standard stars at various positions on the slit. The sky background was then fitted line by line and subtracted from

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TABLE 1

OBSERVING LOG

Object	Exposure Time (s)	P.A. (180° = E-W)
2A0335+096	1800	135°
A496	3000	90, 180
Hydra A	1500	90
S1101	2100	117, 153

the object frames. Flux-calibration was accomplished using wide-slit observations with otherwise identical instrumental setups of flux standards. The standard stars were LTT 377, LTT 1020, and LTT 2415. Atmospheric extinction corrections were derived, but were consistent with the standard CTIO correction, so the standard CTIO correction was used.

We estimated the upper limits on [Ca II] emission by measuring the noise level directly from the data. We fitted smooth functions to the galaxy continua and subtracted these fits to obtain pure emission-line spectra. We then measured the variance of each spectrum at the wavelengths of the [Ca II] lines within bin widths equal to the FWHM of Hα. This method directly estimates the uncertainties in the flux measurement and sky subtraction. We list our results in Table 2.

3. EXPECTATIONS OF [Ca II] EMISSION

Ferland (1993a) has recently shown that dust-free, low-ionization clouds in the narrow-line regions of active galaxies should emit strongly in the [Ca II] lines at 7291 and 7325 Å. Since active galaxies do *not* show strong [Ca II] emission (e.g., Ferland & Persson 1989), the calcium in narrow-line clouds cannot be in the gas phase and thus is probably depleted onto dust grains. Here we argue similarly for cooling-flow nebulae. Using analytical estimates and numerical photoionization models, we calculate the [Ca II] λ7291/Hα ratios expected from dust-free filaments in cooling flows and show that they exceed the upper limits in Table 2 by up to an order of magnitude, strongly suggesting that cooling-flow filaments are dusty.

Ratios of forbidden-line emission to Hα emission in photoionized nebulae are determined by the nebular temperature, the abundance of the emitting ion relative to hydrogen, and the collision strength of the forbidden line. Adopting the collision strengths used in the phtoionization code CLOUDY (Ferland 1993*b*) for [N II] λ6584 (Mendoza 1983) and [Ca II] λ7291 (Chidichino 1981) and the hydrogen recombination-line data from Osterbrock (1989), we find that

$$R_{7291} \equiv \frac{F_{7291}}{F_{\mathrm{H}\alpha}} \approx 0.92 \, \frac{n_{\mathrm{Ca\,II}}}{n_{\mathrm{Ca}}} \, \frac{X_{\mathrm{Ca}}}{2.6 \times 10^{-6}} \, e^{1.97(1-1/T_4)} \, , \quad (1)$$

$$R_{6584} \equiv \frac{F_{6584}}{F_{\mathrm{H}\alpha}} \approx 1.82 \, \frac{n_{\mathrm{N\,II}}}{n_{\mathrm{N}}} \, \frac{X_{\mathrm{N}}}{9.8 \times 10^{-5}} \, e^{2.18(1-1/T_4)} \, , \quad (2)$$

where T_4 is the nebular temperature in units of 10^4 K, F represents line flux, n represents number density, and $X_Z = n_Z/n_{\mathrm{H}}$. The observed values of $F_{6584}/F_{\mathrm{H}\alpha}$ indicate that N^+ is abundant and that $T_4 \approx 1$. At these temperatures, [Ca II] λ7291 emission will be quite strong when Ca^+ is the dominant ionization state of calcium. (The critical densities for collisional deexcitation are $\sim 10^5$ cm^{-3} for λ6584 and $\sim 10^6$ cm^{-3} for λ7291.)

TABLE 2

[N II]/Hα EMISSION-LINE RATIOS AND [Ca II]/Hα UPPER LIMITS

Object	Hα FWHM (Å)	R_{6584} ([N II]/Hα)	R_{7291} ([Ca II]/Hα) (3 σ limit)
2A0335+096	10.0	1.20	<0.025
A496	8.4	1.19	<0.074
Hydra A	12.3	0.86	<0.056
S1101	8.2	1.24	<0.220[a]

[a] [Ca II] wavelengths fall near sky absorption feature.

Photoionization models calculated using CLOUDY (version 84.00, Ferland 1993b) with undepleted solar abundances of metals show that $R_{7291} > 0.1$ for a wide range of incident spectral shapes when $-5 < \log U < -3$. (The ionization parameter U equals the number density of H-ionizing photons divided by the total number density of hydrogen.) Typically, $R_{7291} \sim 0.3$ for $\log U \sim -4$. The spectral shape need only be hard enough to produce sufficient [N II] flux, that is, the spectrum must yield enough heating per ionization to maintain $T_4 \approx 1$. Outside of this interval in U, both R_{7291} and R_{6584} drop as the ionization balance leaves the range appropriate for cooling-flow filaments. Figure 1 shows how these line ratios vary with U for the kinds of photoionization models described in Donahue & Voit (1991).

At the values of U that reproduce the other optical line ratios ($\log U \sim -4.2$ to -3.9; see Donahue & Voit 1991), the predictions for R_{7291} are much higher than our observed upper limits, implying that Ca must be selectively depleted. Reductions in the overall metallicity do not reduce the [Ca II] lines by a proportionate amount. When the metallicity is lower, the nebular temperature must rise so that forbidden-line

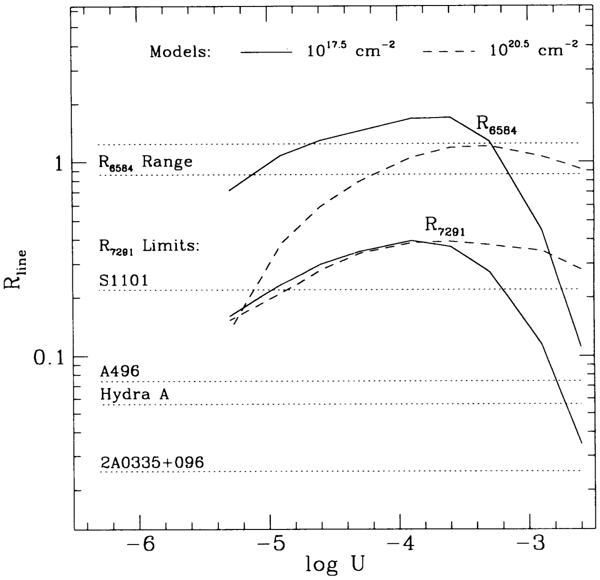

FIG. 1.—Predicted and observed [Ca II] λ7291/Hα (R_{7291}) and [N II] λ6584/Hα (R_{6584}) line ratios from cooling-flow filaments. The curves illustrate the results of CLOUDY (version 84.00, Ferland 1993b) photoionization models of undepleted solar-abundance clouds at different ionization parameters U irradiated by a cooling-flow spectrum. The form of this spectrum when gas begins cooling from 10^7 K is given in Donahue & Voit (1991). *Solid lines* show models of matter-bounded clouds (total H column = $10^{17.5}$ cm^{-2}; $n_{\mathrm{H}} = 300$ cm^{-3}); *dashed lines* show models of thick clouds (total H column = $10^{20.5}$ cm^{-2}; $n_{\mathrm{H}} = 300$ cm^{-3}). At these ionization parameters, the relative strengths of λ7291 and λ6584 are not particularly sensitive to the incident spectral shape, as long as it is hard enough to give $R_{6584} \sim$ 1–2. The dotted lines give our 3 σ upper limits on R_{7291} and the range of R_{6584} values for the four clusters observed here. The upper limits on R_{7291} lie far below the expected emission from dust-free clouds. Apparently the calcium in these clouds is depleted onto dust grains.

cooling still balances photoelectric heating. For R_{7291} to be so low, the gas-phase abundance of Ca must be anomalously small. In our own interstellar medium, calcium can be depleted into grains by factors from ~ 10 to > 1000 (Phillips, Pettini, & Gondhalekar 1984). Such high depletions in cooling-flow filaments would easily reduce the [Ca II] flux below our sensitivity.

Is it possible that the filaments are not photoionized but instead are energized by shocks? Shock models that predict [Ca II] line strengths give $R_{7291} \lesssim 0.1$ for shock velocities $v_s \lesssim 120$ km s^{-1} and $R_{7291} \sim 0.2$ for $v_s = 180$ km s^{-1} (Hartigan, Raymond, & Hartmann 1987), but these shock velocities do not give $R_{6584} \gtrsim 1.0$. Raising this ratio above unity requires high-velocity shocks ($v_s > 200$ km s^{-1}), in which most of the forbidden-line emission arises from *photoionization* of the postshock gas by soft X-ray and EUV radiation emitted nearer the shock front (Binette et al. 1985). Herbig-Haro objects, among the few astronomical sites where [Ca II] has been detected, often show $R_{7291} \sim 0.1$, but R_{6584} does not exceed 0.6 (Dopita 1978). Not only do shocks fail to explain the absence of [Ca II] in the presence of strong [N II] emission, the emitting filaments apparently have avoided undergoing shocks strong enough to destroy the dust grains they seem to contain!

4. IMPLICATIONS FOR THE ORIGIN OF THE NEBULAR GAS

Various independent indicators now show that dust exists in some clusters of galaxies. Broad-band images of the brightest galaxy in nine of 19 cluster cooling flows show evidence for dust bands (McNamara & O'Connell 1992). Sparks, Macchetto, & Golombek (1989) demonstrate that the dust lanes in NGC 4696, at the center of the Centaurus cluster, correlate spatially with its extended Hα nebulosity and suggest that thermal conduction energizes the nebula. Hu (1988, 1992) has demonstrated that the Lyα to Hα emission-line ratios in several clusters lie below case B recombination ratios, implying reddenings of $E_{B-V} \sim 0.2$ above foreground extinction. Also, *IRAS* searches for far-infrared emission from central cluster galaxies (Bregman, McNamara, & O'Connell 1990; Grabelsky & Ulmer 1990) and entire clusters (Wise et al. 1993) have met with varying degrees of success, but the reported detections have low statistical significance, owing to contamination by infrared "cirrus" clouds in our own Galaxy.

The hot ICM itself cannot contain dust in typical Galactic proportions; if its dust-to-gas ratio were similar to the Galactic value, clusters would be opaque in the optical band (e.g., Hu 1992). Dwek, Rephaeli, & Mather (1990) compare the rate at which galaxies inject dust into the ICM with the rate at which hot ions in the ICM sputter the dust and find that only 1% of the dust injected over the history of the cluster currently survives. Hot ions destroy dust even more efficiently in the dense ICM surrounding cooling-flow filaments. Once dust becomes immersed in the hot gas, sputtering will destroy it on a timescale $\sim 10^6 (a_\mu / n_{\rm hot})$ yr, where a_μ is the grain radius in microns and $n_{\rm hot}$ is the density of the hot gas in cm^{-3} (Draine & Salpeter 1979). In the neighborhood of the filaments, $n_{\rm hot} \sim 0.1$ cm^{-3}, implying a brief dust lifetime compared to any dynamical time in the ICM.

Dust injected into the ICM should be destroyed long before a cooling flow could transport it to the center of the cluster. Even if some grains survive the barrage of sputtering ions, demolition of only $\sim \frac{1}{3}$ of the calcium-bearing dust releases enough Ca to make the [Ca II] lines observable in our survey. Apparently, the nebular gas has *never* been part of the hot ICM. The filaments might be energized by the cooling of the ICM, but they are not the condensates themselves. More likely, they are cool clouds that have been stripped from the interstellar media of cluster galaxies and have managed to remain cool as they settled to the center of the cluster.

What alternatives are there to concluding that the filaments are not condensates? Could calcium be anomalously underabundant in clusters? This would be very difficult to arrange, since the prominence of the [S II] lines shows that sulfur is abundant, and S and Ca are produced similarly in massive stars and supernovae. (It is possible, in principle, to estimate the abundance of Ca in gas cooling from 10^7 to 10^6 K from the strength of the [Ca XVI] line at 2731 Å.) Could dust have formed following condensation of the filamentary gas out of the hot ICM? Dust-formation scenarios for explaining the [Ca II] deficiency must allow the filamentary gas to cool below 2000 K, remaining hidden while virtually all the gas-phase calcium accretes onto grains, *before* the gas reheats and lights up as a nebula. Grains can nucleate spontaneously in gases which cool below the condensation temperatures of refractory elements (1000–2000 K), but the low densities of intracluster filaments, compared with those of cool-star winds, make nucleation prohibitively slow. At best, when the sticking probability is of order unity, depletion of metals onto grains that already exist takes at least $10^7 T_2^{-1/2} n_4^{-1} R_d^{-1}$ yr in a cloud of temperature (100 K)T_2, density (10^4 cm^{-3})n_4, and an initial dust-to-gas ratio (0.01)R_d times the Galactic value (Spitzer 1978; Seab 1987). Could the filaments be energized by a mechanism qualitatively different from the photoionization and shock models described here? Perhaps such a mechanism exists, but it must keep $n_{\rm Ca^+} < 0.1 n_{\rm Ca}$ while still generating a high [N II]/Hα ratio. None of these three alternatives appears promising. We encourage further theoretical investigation of the possibility that cool, dusty clouds introduced into the hot ICM might remain cool.

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