

NEW RESULTS CONCERNING THE GALACTIC FOUNTAIN¹

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ABSTRACT

We have calculated the time-dependent, nonequilibrium thermal and ionization history of hot, optically thin, radiatively cooling gas in a one-dimensional, planar, steady-state flow model of the galactic fountain. Consistent with previous work, we find that the calculation of such a flow which neglects photoionization cannot simultaneously reproduce the observed C IV, Si IV, and N V column densities through galactic halo gas. We show, however, that when photoionization is taken into account, a fountain flow *can* match the observations of *both* UV absorption *and* emission lines for a range of ionizing fluxes which depends on the characteristic size of the cooling regions within the flow. We determine what levels of external photoionizing flux, such as that contributed by galactic starlight, supernova remnants, and the metagalactic radiation background, can produce agreement with observational results. Remarkably, we find that the ionizing radiation emitted by the cooling gas itself is sufficient to cause the flow to match the observed column densities and line emission. Such a match implies a fountain flow with initial hydrogen density of $\sim 2 \times 10^{-2} \text{ cm}^{-3}$, outflow velocity of $\sim 100 \text{ km s}^{-1}$, and initial size for the cooling regions of $\sim 1 \text{ kpc}$ or greater.

Key words: galactic fountain model—Milky Way system

1. Introduction

Observations of ultraviolet absorption and emission lines of highly ionized atoms in interstellar gas at large distance from the Galactic plane and of 21-cm emission from high-velocity neutral clouds can be interpreted in terms of the Galactic fountain model of Shapiro & Field 1976. In this model, Galactic halo gas which originates in the disk is shock heated to $T \sim 10^6 \text{ K}$ and flows out of the disk into the halo where it radiatively cools and recombines, loses buoyancy, and falls back toward the Galactic plane. This and subsequent work in the field, such as that of Bregman 1980 and Houck & Bregman 1990, has been summarized recently by Spitzer 1990. In order to study the physical behavior and spectral signature of such a flow, we have recalculated the nonequilibrium radiative cooling, ionization, and recombination of an optically thin gas composed of the 13 elements H, He, C, N, O, Ne, Na, Mg, Si, S, Ca, Fe, and Ni (Shapiro & Benjamin 1991). We use the abundances of Allen 1973 and the atomic data of Raymond & Smith 1977 and Raymond 1987. We have solved the ionization balance rate equations together with the equation of energy conservation for a gas cooling from 10^6 K to 10^4 K at either constant density (isochoric), constant pressure (isobaric), or the intermediate case where the cooling is initially isobaric with a transition to iso-

choric. The type of cooling depends on the assumed size, D , of the cooling region. Regions for which the sound crossing time is longer (shorter) than the cooling time for all temperatures will be isochoric (isobaric) throughout their cooling history. The intermediate case corresponds to length scales for which the sound crossing time exceeds the cooling time at some intermediate temperature between 10^4 K and 10^6 K . We also include the effects of photoionization by an ambient field contributed by galactic stars and supernova remnants and by the metagalactic radiation background, as well as the effect of diffuse emission by the flow.

For each case we calculate the UV absorption and emission-line spectrum as well as the X-ray flux and total ionizing flux for comparison with observations. This allows us to estimate the local mass flux, initial density, and initial outflow velocity required in order for such a galactic fountain flow to match the data. We also apply the results of these calculations to the question of the origin of quasar absorption lines in Galactic halo clouds at higher redshift, considering the effects of different types of incident radiation fields.

2. Calculations and Results

2.1 *The Galactic Fountain and Milky Way Halo Gas*

We have considered a one-dimensional, plane-parallel, steady-state flow of optically thin, radiatively cooling halo gas out of the Galactic disk with an initial velocity,

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v_0 , and initial hydrogen density, $n_{\text{H},0}$. The mass flux of this flow is given by $\dot{M} = 24 f n_{-2} v_{100} \mathcal{M}_{\odot} \text{ yr}^{-1}$ where $n_{-2} = (n_{\text{H},0}/10^{-2} \text{ cm}^{-3})$, $v_{100} = (v_0/100 \text{ km s}^{-1})$ and f is the fraction of the Galactic disk covered by such a flow such that the total area of the flow is $f \pi R_{\text{disk}}^2$, where $R_{\text{disk}} = 15 \text{ kpc}$. The gas starts in ionization equilibrium at a temperature of 10^6 K . The column density of an ion i of element X along a line of sight perpendicular to the flow direction is given by $N(X^i) = n_{\text{H},0} v_0 \int y_{X+i} dt$, where $y_{X+i} = n(X^i)/n_{\text{H}}$ is the volume density of the ion relative to hydrogen. For cases without photoionization, the column density of ions of interest reaches an asymptotic value at times greater than a few initial cooling times. For cases with photoionization, however, the gas relaxes to thermal and ionization equilibrium, and the column density of some ions will continue to grow in proportion to time for t greater than this relaxation time.

In Figure 1(a) and (b) we present some results for the column densities of C IV, N V, and Si IV and the temperature versus total H column density into the flow, together with the observed column density ratios for Milky Way halo gas from Savage 1988 and Savage & Massa 1987. For cases which include an external incident radiation field we adopt the spectrum of Bregman & Harrington 1986 and vary the flux level by adjusting the ionization parameter $\Gamma_0 = n_{\gamma}/n_{\text{H},0}$, where n_{γ} is the number density of H ionizing photons in the external radiation field. We take advantage of a scaling property in these results such that, for a fixed spectral shape and value of Γ_0 , the results for different values of v_0 and $n_{\text{H},0}$ are the same if plotted against $N(\text{H})/v_0 = n_{\text{H},0} t$.

Our results *without* photoionization agree reasonably well with those of Edgar & Chevalier 1986 and Shapiro & Moore 1976, although we include the effects of charge

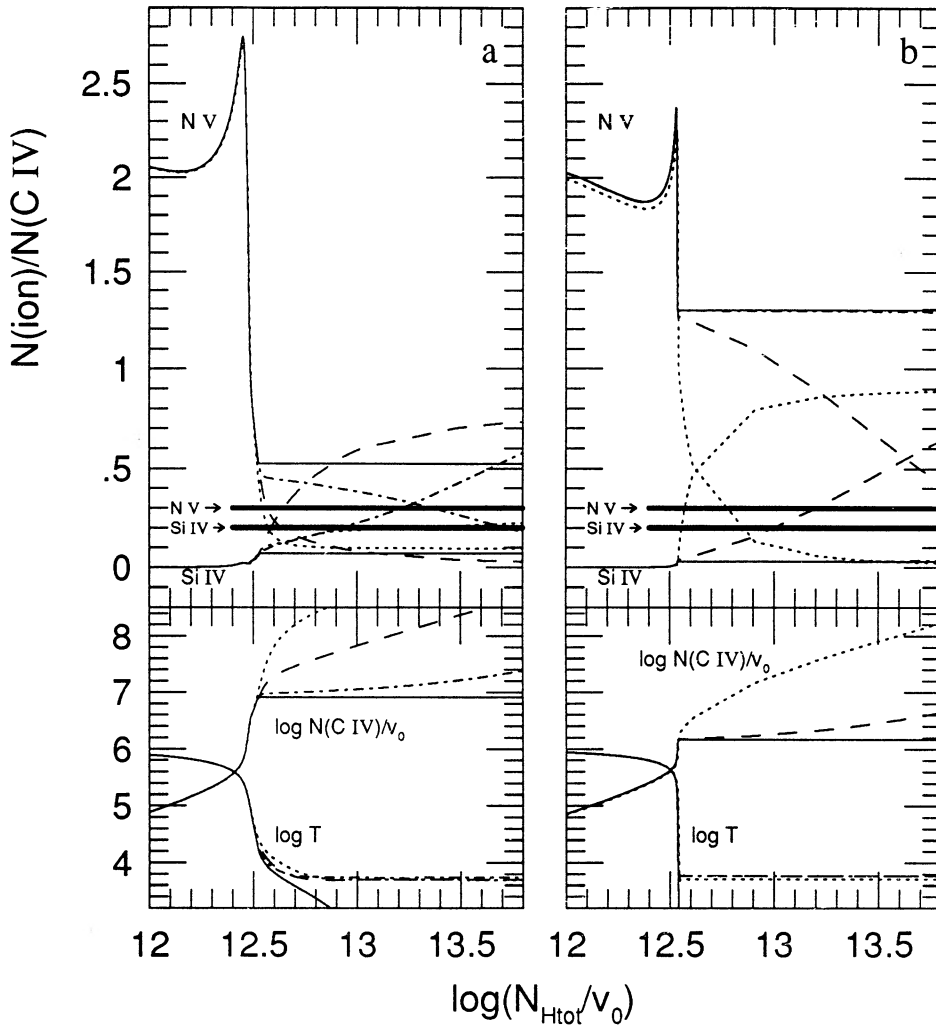


FIG. 1—(a) (Upper panel) Column density ratios $N(\text{N V})/N(\text{C IV})$ (descending curves) and $N(\text{Si IV})/N(\text{C IV})$ (ascending curves) versus $N(\text{H})/v_0 (\text{cm}^{-3} \text{ s})$ for isochoric cases with no photoionization (solid line), and with an external photoionization field with $\log \Gamma = -1.2$ (dotted), $\log \Gamma = -2.2$ (dashed), and $\log \Gamma = -3.1$ (dash-dot). The observed column density ratios are indicated with bold lines. (Lower panel) Temperature and $N(\text{C IV})/v_0$ versus $N(\text{H})/v_0$. (b) Same as (a), but with isobaric cooling, for cases with no photoionization (solid line), and an external photoionization field with $\log \Gamma = -0.2$ (dotted), $\log \Gamma = -1.2$ (dashed), and $\log \Gamma = -2.2$ (dash-dot).

exchange while they did not. We find that at no point in the flow can we match both of the column density ratios $N(\text{N v})/N(\text{C iv}) \approx 0.3$ and $N(\text{Si iv})/N(\text{C iv}) \approx 0.2$ reported by Savage 1988. By including photoionization effects, however, we do succeed in matching these ratios. For cases *with* external photoionization, the range of cloud sizes and ionization parameters for which we are able to match the observed column density ratios within ± 0.05 is given in Figure 2. For an isochoric region, for instance, we find that the ionization parameter must lie in the range $10^{-2.0} \geq \Gamma_0 \geq 10^{-2.6}$.

For each case, we calculate the emergent spectrum of the cooling fountain flow by integrating between the start of the flow and the point at which the column density ratios match the observed values. For the emergent flux, a convenient scaling property exists such that the quantity $\phi_\nu = I_\nu/n_{\text{H},0}v_0$ is constant with respect to changes in $n_{\text{H},0}$ and v_0 , where I_ν is the emergent intensity at frequency ν . We find that in order to match the observed intensity of C iv and O iii] emission lines (Martin & Bowyer 1990) at the same time as the column density ratio constraints are satisfied, $n_{\text{H},0} \approx 2 \times 10^{-2} \text{ cm}^{-3}$ and $v_0 \sim 100 \text{ km s}^{-1}$ are required. This density, taken together with the minimum value of the ionization parameter in Figure 2, implies an ionizing flux level that exceeds the flux estimated from H α observations of neutral clouds in the halo by Kutyrev & Reynolds 1989 by a factor of ~ 10 (for $D \gtrsim 1 n_{-2} \text{ kpc}$) and by larger factors for smaller D . However, such limits are subject to reinterpretation if the neutral halo gas ob-

served in H α emission was actually exposed to an attenuated or diluted version of the flux which ionizes the gas in the fountain flow.

A remarkable new result we have found is that photoionization by radiation emitted by the cooling fountain gas itself is capable of producing column density ratios that match the observed values, as long as the size of the cooling regions is large enough ($D \gtrsim 1 n_{-2} \text{ kpc}$) to be roughly isochoric. The flux of H ionizing photons produced in such a flow corresponds to $\Gamma_0 \sim 10^{-2.9}$ (the value of Γ_0 is lower than the external flux levels required as described above due to a different spectral shape). The C iv emission-line intensity is then matched with a value of $n_{\text{H},0}$ similar to that required for the external photoionization case above. Such a scenario is in closer agreement with the observational limit of Kutyrev and Reynolds. In short, a cooling fountain flow can explain both the observed UV absorption and emission lines of Galactic halo gas by absorbing its own photoionizing emission as it cools, if $n_{\text{H},0} \sim 2 \times 10^{-2} \text{ cm}^{-3}$ and $v_0 \sim 100 \text{ km s}^{-1}$, and the initial size of the cooling region is $\sim 1 \text{ kpc}$ or more. One of the most encouraging aspects of this result is that it provides a natural explanation for the constancy of the Si iv/C iv ratio along different lines of sight reported by Savage & Massa 1987.

2.2 The Galactic Fountain and Quasar Absorption Lines

Finally, we have examined under what conditions radiatively cooling halo gas like this can explain the ob-

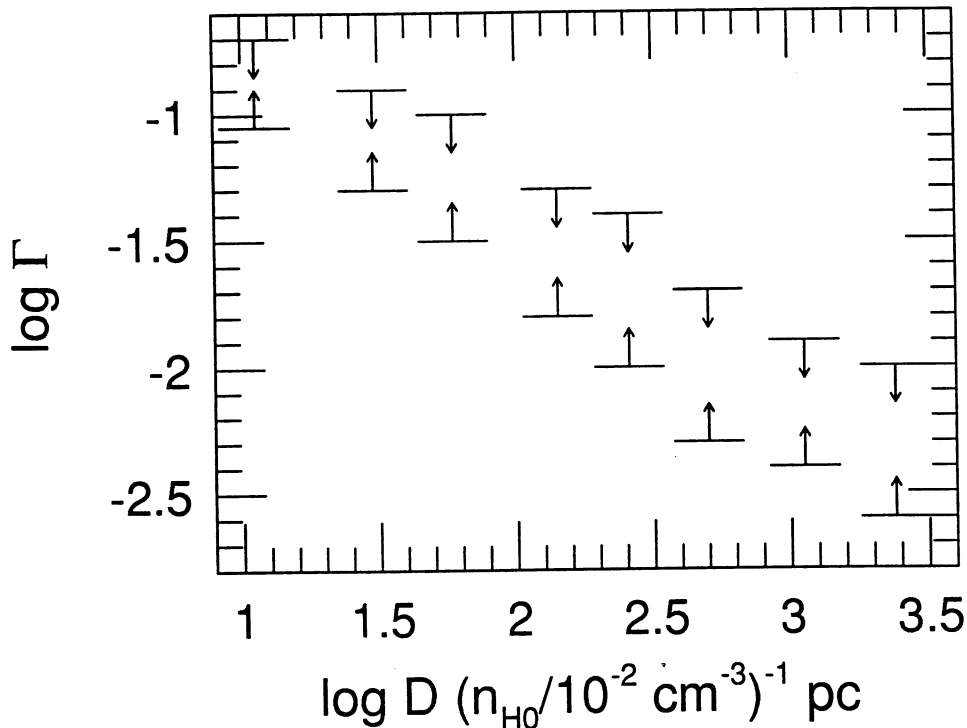


FIG. 2—Range of required flux level of the incident external photoionization spectrum (assumed to have the spectral shape given by Bregman & Harrington 1986) for a given size cooling region in the fountain flow.

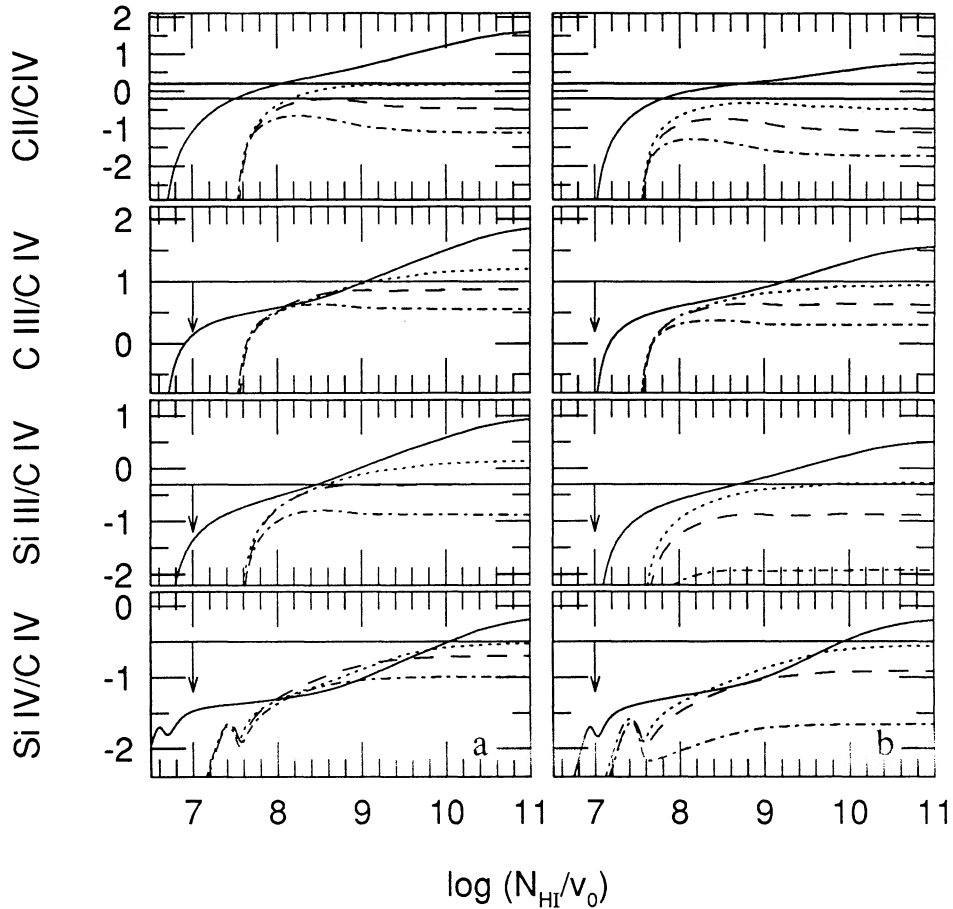


FIG. 3— $3-\log(N(\text{ion})/N(\text{C IV}))$ for isochorically cooling gas with a galaxy-type spectrum from Bregman & Harrington 1986 with $\log \Gamma = -2.7$ (solid), $\log \Gamma = -2.0$ (dotted), $\log \Gamma = -1.6$ (dashed), and $\log \Gamma = -1.2$ (dash-dot). The observed range for C II is indicated, and upper limits for C III, Si III, and Si IV are indicated with a downward arrow. (b) Same as (a), but with an attenuated AGN-source metagalactic spectrum from Giroux & Shapiro 1990.

served column densities of H I, C II, C III, Si III, Si IV, and C IV for heavy-element absorption systems at $z \sim 3$ seen in the spectra of QSOs. Figure 3 shows the results of our calculation for an isochoric, steady-state cooling flow as described above. We have also plotted the observed values for a Lyman-limit cloud with $N(\text{H I}) \cong 10^{17.5} \text{ cm}^{-2}$ at $z_{\text{abs}} = 2.9676$ in the spectrum of PKS 2126-158 ($z_{\text{em}} = 3.27$) reported by Sargent, Steidel & Boksenberg 1990. Again, we found that gas cooling without photoionization, or even gas cooling isobarically with a photoionization parameter as large as $10^{-1.0}$, could not match the observed column density ratios. However, gas cooling isochorically in the presence of a strong-enough, but reasonable, external photoionization field and $\sim 1/100$ th solar metallicities could successfully match all of the column density constraints. We also examined the effect of different possible types of photoionizing spectra. A normal galaxy-type spectrum like that of Bregman and Harrington required $\Gamma_0 \sim 10^{-1.8}$, while a spectrum resulting from AGN-type sources emitting throughout a cosmologically expanding intergalactic medium as calculated by Giroux & Shapiro 1990 required $\Gamma_0 \sim 10^{-2.0}$. These flux levels are signifi-

cantly higher than that of the radiation emitted by the flow itself. Hence, unlike the case of our own Galactic halo gas, self-ionization of the fountain flow is not sufficient to account for the observed quasar absorption lines at high redshift.

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REFERENCES

- Allen, C. W. 1973, *Astrophysical Quantities* (London, The Athlone Press)
- Bregman, J. N. 1980, *ApJ*, 236, 577
- Bregman, J. N., & Harrington, J. P. 1986, *ApJ*, 309, 833
- Edgar, R. J., & Chevalier, R. A. 1986, *ApJ*, 310, L27

- Giroux, M. L., & Shapiro, P. R. 1990, in *Physical Processes in Fragmentation and Star Formation*, ed. R. Cappuzzo-Dolcetta, C. Chiosi, & A. DeFazio (Dordrecht, Kluwer Academic Publishers), p. 71
- Houck, J. C., & Bregman, J. N. 1990, *ApJ*, 352, 506
- Kutyrev, A. S., & Reynolds, R. J. 1989, *ApJ*, 344, L9
- Martin, C., & Bowyer, S. 1990, *ApJ*, 350, 242
- Raymond, J. C. 1987, private communication
- Raymond, J. C., & Smith, B. W. 1977, *ApJS*, 35, 419
- Sargent, W. L. W., Steidel, C. C., & Boksenberg, A. 1990, *ApJ*, 351, 364
- Savage, B. D. 1988, in *QSO Absorption Lines: Probing the Universe*, ed. J. C. Blades, D. A. Turnshek, and C. A. Norman (New York, Cambridge University Press), p. 195
- Savage, B. D., & Massa, D. 1987, *ApJ*, 314, 380
- Shapiro, P. R., & Benjamin, R. A. 1991, *ApJ*, submitted
- Shapiro, P. R., & Field, G. B. 1976, *ApJ*, 205, 762
- Shapiro, P. R., & Moore, R. T. 1976, *ApJ*, 207, 460
- Spitzer, L. 1990, *ARA&A*, 28, 71