THE SPECTRUM OF COOLING GAS IN THE GALACTIC FOUNTAIN[1]

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Abstract

We have calculated the time-dependent, nonequilibrium thermal and ionization history of gas cooling radiatively from $10^6 K$ in a one-dimensional, planar, steady-state flow model of the galactic fountain, including the effects of radiative transfer. Our previous optically thin calculations explored the effects of photoionization on such a flow and demonstrated that self-ionization was sufficient to cause the flow to match the observed galactic halo column densities of C IV, Si IV, and N V and UV emission from C IV and O III in the constant density (isochoric) limit, which corresponds to cooling regions homogeneous on scales $D_0 \gtrsim 1\,kpc$. Our new calculations which take full account of radiative transfer confirm the importance of self-ionization in enabling such a flow to match the data but allow a much larger range for cooling region sizes, i.e. $D_0 \gtrsim 15\,pc$. For an initial flow velocity $v_0 \sim 100\,km/s$, comparable to the sound speed of a $10^6 K$ gas, the initial density is found to be $n_{H,0} \sim 2 \times 10^{-2}\,cm^{-3}$, in reasonable agreement with other observational estimates of ionized halo gas, and $D_0 \sim 40\,pc$. We also compare predicted $H\alpha$ fluxes, total ionizing flux, free-free radio emission, and broadband X-ray fluxes with observed values, as well as the application of fountain flows to explain Lyman limit quasar metal absorption lines at higher redshift.

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 (HVC's) can be interpreted in terms of the galactic fountain model [1]. In this model, galactic halo gas which originates in the disk is shock-heated to $T \sim 10^6 K$ 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 have been summarized recently by [2]. We have recalculated the nonequilibrium radiative cooling, ionization, and recombination in such a flow composed of the 13 elements H, He, C, N, O, Ne, Mg, Si, S, Ar, Ca, Fe, and Ni. We have improved upon our previous calculations in [3] and [4] by taking account of optical depth through the flow. We calculate UV absorption and emission line spectra, the X-ray flux, total ionizing flux, $H\alpha$ flux, and free-free radio emission at 53 GHz for comparison with observations. This allows us to estimate the mass flux, initial density, and initial outflow velocity required to match the data. We also discuss the application of fountain calculations to explain high ionization QSO metal absorption lines for Lyman-limit systems at high redshift.

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2. The Calculation

We consider a 1-D, planar steady-state flow of halo gas cooling radiatively from an initial condition of coronal ionization equilibrium at $T_0 = 10^6 K$ with an initial velocity, v_0, and initial hydrogen density, $n_{H,0}$. The galactic mass flux in this flow to each side of the disk is $\dot{M} = 24\, f n_{-2} v_{100}\, M_\odot/yr$, where $n_{-2} = (n_{H,0}/10^{-2} cm^{-3})$, $v_{100} = (v_0/\,100 km/s)$ and f is the fraction of the galactic disk covered by such a flow such that the total area of the flow is $f\pi R_{disk}^2$, where $R_{disk} = 15 kpc$. We solve the equations of energy conservation and radiative transfer along with 181 ionization balance rate equations, with the elemental abundances of [5] and the atomic data of [6] and [7].

To simplify the dynamical evolution, we assume that as gas cools from $10^6 K$ to $10^4 K$, it does so at either constant density (isochoric), constant pressure (isobaric), or the intermediate case where the cooling is initially isobaric with a transition to isochoric. The type of cooling depends upon the assumed size, D_0, 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. For $D_0 \lesssim 0.4(n_{-2})^{-1} pc$ or $D_0 \gtrsim 2(n_{-2})^{-1} kpc$, cooling is always isobaric or isochoric, respectively. For intermediate cases, the initial D_0 can be related to the size, D_{tr}, at the transition time, by $n_{H,tr} D_{tr}^3 = n_{H,0} D_0^3$. Once the gas has cooled to $\sim 10^4 K$, it gradually recombines and self-shields, thereby terminating the presence of highly ionized species. We therefore do not carry our calculations beyond this point.

Several scaling properties enable us to limit the number of separate calculations required to span the range of input parameters $n_{H,0}$, v_0, and D_0. For a given product $(n_{H,0} D_0)$, the quantity $\phi_\nu = F_\nu / n_{H,0} v_0$ is constant with respect to changes in $n_{H,0}$, D_0, and v_0, where F_ν is the emergent flux at frequency ν. The ionization parameter, $U = n_\gamma / n_H$, where n_γ is the number density of H ionizing photons in the emergent flux, is $U = (v_0/c)\,\phi$, where $\phi = \int \phi_\nu d\nu$. This ϕ, the number of H ionizing photons emergent per H atom in the flow, is only weakly dependent on D_0. For given values of $(n_{H,0} D_0)$ and v_0, the time evolution of any fluid element is the same for different values of $n_{H,0}$ if plotted against $(n_{H,0} t)$. For steady-state planar flow, the time history of any single fluid element gives the spatial variation through the flow by its position as a function of time t. The H column density accumulated between its position at $t = 0$ and at t is just $N_H(t) = n_{H,0} v_0\, t\, cm^{-2}$, however. Hence, the scaled time $(n_{H,0} t)$ may also be interpreted directly as a scaled spatial coordinate, with length measured nonuniformly in units of N_H / v_0.

3. Galactic Halo Absorption Line Column Densities

The column density of species i along a line parallel to the flow is $N_i = v_0 \int y_i d(n_{H,0} t)$, where $y_i = n_i / n_H$ is the number density of the ion relative to H, where the integral is over the time history of a single fluid element. As the gas cools and recombines, the N_i's for all non-neutral species approach asymptotic values. For each $(n_{H,0} D_0)$, we solve for the value of v_0 (and hence U) required to match the observed column density of C IV. We then compare our resulting theoretical column densities of Si IV and N V to the average

observed values reported by [8], $N(Si\,IV)/N(C\,IV) = 0.33 \pm 0.19$ and $N(N\,V)/N(C\,IV) = 0.28 \pm 0.16$. These match the data for all $(n_{H,0}D_0)$-values, $n_{-2}D_0 \gtrsim 8\,pc$. The required flow velocity is then $log_{10}\,v_0\,(km/s) \cong -0.33\,log_{10}\,n_{-2}D_0(pc) + 2.55$ for $2\,kpc \gtrsim n_{-2}D_0 \gtrsim 8\,pc$, and $v_0 \cong 30 km/s$ for $n_{-2}D_0 \gtrsim 2\,kpc$. For $v_0 \sim 100\,km/s$, an outflow velocity comparable to the sound speed of a $10^6 K$ gas, this gives $D_0 \sim 80(n_{-2})^{-1} pc$. For $n_{-2}D_0 \lesssim 8\,pc$, the column density ratios do not match the observed values for any v_0. The difference between these results and our previous optically thin results ([3] [4]) can be attributed to the improved treatment of radiative transfer. Our success in reproducing the observed column densities with a self-ionized flow explains naturally the constancy of the Si IV/C IV and N V/ C IV ratios along different lines of sight reported by [8]. Calculated column densities of a few species of interest are shown in Table 1. Such a flow, for example, also predicts N(O VI)/ N(C IV) ranging from 3.1 ($n_{-2}D_0 = 8pc$) to 1.9 ($n_{-2}D_0 \gtrsim 2kpc$). This ratio is consistent with recently reported [9] UV absorption line spectra of 3C273 taken by the Hopkins Ultraviolet Telescope.

TABLE 1 Column Densities ($10^{14} cm^{-2}$) of Ions in Galactic Halo

Ion	$n_{-2}D_0 = 40pc$	$135pc$	$250pc$	$\geq 2000pc$
C IV	1.00	1.00	1.00	1.00
N III	9.81	5.06	4.70	7.64
N V	0.15	0.14	0.14	0.14
O VI	3.02	2.28	2.06	1.86
Si III	2.56	2.39	2.39	2.84
Si IV	0.25	0.21	0.21	0.24

4. Galactic Halo Emission Line Intensities and Broadband Fluxes

For each $(n_{H,0}D_0)$-value which reproduces the observed absorption line column densities, the calculated normalized emergent flux, ϕ_ν, is independent of $n_{H,0}$. We solve for $n_{H,0}$ by matching our calculated intensity for the C IV emission line at 1549 Å to the intensity observed toward the Galactic pole by [10]. This yields $log_{10}\,n_{-2} \cong 0.52\,log_{10}\,D_0(pc) - 0.91$, for $500\,pc \gtrsim D_0 \gtrsim 15\,pc$. For $n_{-2}D_0 \gtrsim 2\,kpc$, the evolution is always isochoric and $n_{H,0} \sim 4 \times 10^{-2} cm^{-3}$. The predicted ratio of O III] 1662 Å to the C IV line agrees with the value observed by [10] as well. Other calculated line intensities are given in Table 2. Our O VI intensity exceeds by ~ 3 a preliminary upper limit reported by [11] for a different line of sight.

Limit on Halo Ionizing Flux? Observations of $H\alpha$ emission from the direction of an HVC believed to be in the halo implies an upper limit to the ionizing flux incident on that cloud [12]. The upstream ionizing flux emergent from our calculated flow exceeds this limit by ~ 6. Our calculations are consistent with this limit, however, if the HVC observed in $H\alpha$ emission was actually exposed to an attenuated or geometrically diluted version of our calculated flux. If we identify only the recombined, self-shielded part of our flow with the observed neutral clouds, for example, the calculated emergent $H\alpha$ flux from that gas does satisfy this observational limit.

TABLE 2 Calculated Specific Intensities of Emission Lines in the Galactic Halo ($10^{-8} ergs\, s^{-1}\, cm^{-2}\, sr^{-1}$)

Ion	λ Å	$D_0 = 20pc$	$65pc$	$102pc$	$\geq 500pc$
O VI	1033.8	61.36	54.46	49.50	46.28
C IV	1549.0	6.45	6.45	6.45	6.45
C III	977.0	3.74	3.79	3.84	4.03
N V	1240.0	3.68	3.42	3.34	3.30
O V	1218.0	3.62	3.13	3.15	3.32
O IV	1402.0	2.84	2.83	2.91	2.94
C III	1910.0	4.20	3.24	3.10	3.21
Ne VI	1006.0	2.07	1.77	1.44	1.35
O III]	1662.0	1.16	1.08	1.08	1.23
C II]	2325.0	2.78	0.92	0.87	1.15

Diffuse High-Latitude $H\alpha$ Emission ("Reynolds Layer")? Our cooling fountain gas accounts for $\sim 40\%$ of the integrated $H\alpha$ flux along a line perpendicular to the galactic plane derived from a survey of diffuse $H\alpha$ emission [13]. Half of this is $H\alpha$ emergent from the flow itself; half is "reprocessed" ionizing radiation from the flow in the form of recombination radiation by the top of the "thick H I layer" (e.g. "Lockman layer") below.

Galactic Halo Free-Free Emission? The analysis on which the recent COBE discovery of CMB temperature anisotropy is based [14] assumed the galactic radiation background at 53 GHz is dominated by free-free emission from the so-called "Reynolds layer", interpreted as ionized H at $8000K$. Our fountain flow emits free-free at 53 GHz with an intensity which implies a ratio of antenna temperature to its $H\alpha$ emission of $T_A/I_{H\alpha} = 3.3\mu K/R$, where $R = 1 Rayleigh = 2.42 \times 10^{-7} ergs\, s^{-1}\, cm^{-2}\, sr^{-1}$. Multiplying by the direct fountain $I_{H\alpha}$ alone, we find $T_{A,fountain} = 0.8\mu K$, or 1/3 of that attributed previously to the "Reynolds layer". This may be important for future interpretation of COBE CMB anisotropy results.

High Latitude Broadband X-ray Emission? Broadband X-ray fluxes are calculated and converted to detector countrates in Table 3. The emergent flux, unattenuated by foreground absorption, accounts for only $\sim 25\%$ of the observed M-band ($.4 - 1.1\, keV$) flux, while exceeding the flux in the lower energy bands. A reasonable amount of attenuation due to intervening absorption, corresponding to $N(H\,I) \sim$ a few $\times\, 10^{20} cm^{-3}$ (*c.f.* [10]), would reduce the calculated fluxes so as to agree with observed limits (*c.f.* [15]).

X-ray Luminosity vs Fountain Flow Covering Fraction and ISM Global Energy Balance? For covering fraction f=1, our fountain flow emits $L_{X-ray}(\geq .3keV) \sim$ several$\times\, 10^{39}\, ergs\, s^{-1}$, exceeding by ~ 10 the existing upper limits on X-ray emission from external edge-on spiral galaxies [19]. If such a limit applies to the Milky Way, then we require $f \lesssim 0.1$. This yields $\dot{M} \lesssim 2.4 M_\odot/yr$, in agreement with estimates of $\dot{M}$ associated with infalling HVC's. However, the total fountain flow energy flux accounts for most of the total estimated SN energy input into the ISM only if $f = 1$. This possible discrepancy may be resolved if current limits on L_{X-ray} are too low, if the actual fountain flow initial $T < 10^6 K$, if halo and disk gas attenuate the X-rays, or if $f = 0.1$ but the SN energy input is balanced by some other

loss mode (e.g. adiabatic expansion losses in the halo.)

TABLE 3 Calculated Unattenuated X-ray Fluxes

Band	$D_0 \lesssim 100pc$	$\geq 500pc$	$\lesssim 100pc$	$\geq 500pc$	Observed[d]
B(0.1-0.19 keV)	5.2e-7[c]	3.4e-7[c]	2200[a]	1400[a]	100[a]
C(0.12-0.28 keV)	5.3e-7[c]	3.6e-7[c]	3500[a]	2500[a]	250 [a]
M(0.44-1.1 keV)	9.8e-9[c]	7.6e-9[c]	9.5[a]	7.4[a]	25[a]
ROSAT(0.07-0.28 keV)	8.0e-7[c]	5.5e-7[c]	2.0e-2[b]	1.3e-2[b]	9e-4[b]
ROSAT(0.28-3 keV)	7.9e-8[c]	5.7e-8[c]	6.1e-5[b]	4.6e-5[b]	1e-4[b]

[a] $counts\, s^{-1}$, response function from [16]. [b] $counts\, s^{-1}\, arcmin^{-2}$, PSPC response function from [17]. [c] $ergs^{-1} cm^{-2} sr^{-1}$, total between band limits (flat response). [d] [15], [18].

5. QSO Absorption lines and the Galactic Fountain

If, as widely believed, observed QSO absorption lines of Lyman limit systems originate in the gaseous halos of intervening galaxies, then it is reasonable to ask whether the same kind of cooling flow described above can explain these absorption lines at higher redshift. We compare to column densities observed at $z_{abs} = 2.9676$ in the spectrum of Q2126-1551 [20]. We use relative metal abundances of [5], but the overall metal abundance relative to H is adjusted to match the observed ratio N(C IV)/N(H I) at the point in the flow where $N(H\,I) = 10^{17.35} cm^{-2}$. We include the effect of an external photoionizing flux as well as self-ionization. We take the spectral shape calculated for a normal, present-day galaxy like our own [21] as an example of a possible external photoionizing spectrum for a galactic halo. The absolute flux level of this spectrum parameterized by U_0, the ionization parameter, is adjusted to match the observed column densities. The level of self-ionizing flux is determined by v_0. We present only isochoric cases.

For $v_0 \lesssim 50\, km/s$, external radiation dominates the total ionizing flux. Matching the observed column density ratios then requires $log\, U_0 \sim -1.8$ with a metallicity $log(Z/Z_\odot) \sim -2.4$, in good agreement with our optically thin results [4]. Our improved radiative transfer calculations here also find that, for $v_0 \sim 125\, km/s$ and $log(Z/Z_\odot) \sim -1.7$, self-ionization alone, without any external flux, can match the observed column densities. Such a velocity is consistent with the expectations for a fountain flow in our own present-day galactic halo. This encourages us to think that a galactic fountain may be relevant to the description of quasar metal absorption line systems at high redshift, where high redshift systems have low metallicities. If the detection of O VI absorption recently reported [22] based upon a composite spectrum for many C IV absorption line systems is correct, this favors a galactic fountain origin for the gas responsible, rather than static, equilibrium, photoionized gas clouds. The latter do not produce enough O VI, while our fountain flow predicts ratios $N(O\,VI)/N(C\,IV) = 3.0$ and $N(N\,V)/N(C\,IV) = 0.20$ for the Lyman limit system at z=2.9676 described above.

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