HOT GAS IN GALACTIC HALOES AND WINDS

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I. Introduction At this time we have no direct evidence for the presence of hot gaseous haloes or winds associated with galaxies. We do know that hot gas exists in conjunction with cold gas in the disks of the spirals and that this gas is hot enough to form a substantial corona. There are also a number of indirect observations which would suggest that hot gas flows and possibly bound hot gas occur in both elliptical and spiral galaxies.

In the case of elliptical galaxies the expected accumulated mass loss from the stars is not observed. Typical upper limits to the mass of cold gas at less than 10^4 °K are around 10^8 $M_\odot$ based on 21cm emission studies of the galaxies (reviewed by Van Woerden 1977). We would expect almost two orders of magnitude more material than this to have been ejected from the stars. Burke (1968), Johnson and Axford (1971) and Mathews and Baker (1971) postulated the existance of a hot galactic wind with temperatures of a few times 10^6 °K powered by supernovae, in order to clear material from these galaxies. The evidence for hot galactic haloes around spiral galaxies is even more indirect and is based on the existance of high latitude cold clouds in our own galaxy. The velocities and number of these clouds imply that they almost certainly lie high above the galactic cold gas which extends only to a height of 130 Pc in the solar neighborhood. Spitzer therefore suggested in 1956 that an intercloud gas would have to exist to keep these clouds confined, and that to have such a large scaleheight it would have to be hot with temperatures of around 10^6 °K. (An alternative suggestion by Pickelner (1955) was that the halo was cold but supported by turbulent velocities of around 70 km s^{-1}.) The Spitzer Halo was assumed to be maintained by energetic particles from SN in the plane.

[Alternative cold mechanisms have been put forward. Ipavich (1975) has suggested that a cold wind could be driven from ellipticals by out streaming cosmic rays and Collins and Weisheit (1976) have discussed magnetically supported cold coronae in our own galaxy.]

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With our new observational and theoretical understanding of the gas in the disk and in particular with the discovery of a hot gas component which itself has temperatures of around 10^6 °K (see reviews by Cox and Jenkins in this volume) theoretical models of the corona have recently been reexamined. In the disk the main source of energy is now thought to be direct dynamical energy input of supernovae, analagous to the suggestion of supernova-driven winds in elliptical galaxies. In the spiral galaxy disk, however, the amount of cold gas is sufficiently large that the energy injection can mostly be radiated away (McKee and Ostriker 1977); if the cold gas is once eliminated however a self consistent hot wind will form and cold gas may not be able to reestablish itself. This is the case that presumably applies to ellipticals and possibly SOs and spiral haloes.

The presence of the hot disk gas implies that, in the absence of a Spitzer corona, there will be substantial gas flow from the galaxy. This in turn will either form a bound corona itself, an outflowing wind or a cyclic fountain where the gas flows out, cools down and falls back in again.

<u>II. Present Observational Constraints on a Galactic Halo</u> Before going on to a more theoretical discussion I wish to review recent observations relevant to the corona of our own galaxy.

For relatively cool gas with ($T \lesssim$ few 10^5 °K) high dispersion optical measurements and IUE UV absorption line studies on Magellanic cloud stars, cores of globular clusters, and the nuclei of external galaxies have been made which supplement the halo star observations.

<u>a. Hot Gas</u> We now know that most of the 250 eV soft X-rays are local in origin and there is no evidence that any emission comes from the corona. Table 1 shows a plausible constraint based on X-ray fluxes at the south galactic pole, making an allowance for the local emission based on the paper of Hayakawa <u>et al</u> (1978).

An additional new constraint comes from N V absorption line studies of extragalactic objects which would sample gas at around a few times 10^5 °K. This provides a matching constraint on the density of the hot gas. I have based the estimate on the upper limit to the equivalent widths quoted by Savage and de Boer (1978). For broad features difficulties in continuum fitting make this rather uncertain and the upper limits should possibly be a factor of 2 or 3 higher. The observations do provide fairly tight constraints, however, with the weakest point being at around 5×10^5 °K. They also imply that the pressure in the halo is less than or comparable to that in the disk ($(\frac{P_{disk}}{k_B}) \approx$ few $\times 10^3$ cm^{-3} °K, Field 1974).

Table I. Constraints on Hot Galactic Halo

Temperature (Kelvin)	Scaleheight(1) (kpc)	Density Bound (cm^{-3}) $<n>$ or $<n^2>^{1/2}$
2×10^5	3	3×10^{-4} NV(2)
5×10^5	4	few $\times 10^{-3}$
10^6	7.5	8×10^{-4} SXR(3)
2×10^6	15	5×10^{-4}

(1) From Spitzer (1956)

(2) Assuming $N(NV) \leq 5 \times 10^{13}$ cm^{-2} (Savage and de Boer 1979)

(3) Assuming emission measure $\leq 5 \times 10^{-3} \left\{\frac{10^{-23} \text{ergs cm}^3 \text{s}^{-1}}{E_{44-70}}\right\} \left\{\frac{F_{250ev}}{100}\right\}$

where E is the emissivity in the 44-70 Å band and F the flux at 250 ev in cm^{-2} s^{-1} str^{-1} keV^{-1}

b. Cold Gas in the Corona Recent improvements in optical spectroscopy and the advent of the IUE satellite have allowed studies of extragalactic objects at relatively high resolution (20 - 30 km/s). In particular, detailed information of the structure of gas along the lines of sight to many Magellanic cloud stars has now been obtained (Blades 1979, Walborn 1979, Songaila and York 1979, Savage and de Boer 1979).

Concentrating on R136 = Hd 38268 = S Dor (l = -32°, b = 280°), Blades observes intermediate velocity components in this LMC star at

V_{LSR} = +70, +123?, +149? km/s

$N(Ca\ II) = 10^{12}$ cm^{-2} N (NaI) = few $\times 10^{11}$ cm^{-2}

FWHM $\leq$ 10 km/s

The Na/Ca ratio strongly suggests that calcium in the 70 km/s cloud is relatively undepleted. If we assume that the Ca II is the dominant ionization stage and that calcium is present in cosmic abundances (2×10^{-6} by number, Allen 1973) this implies a column density of 10^{18} cm^{-2} (a minimum estimate). Components at such a velocity are very rare in the plane and this is almost certainly a cloud in the corona.

We may tentatively identify these components with the high velocity wings seen in observations by Savage and de Boer (since these coincide in velocity it is tempting to assume that the clouds are highly ionized and the wings are blends of the cloud components at the rather poorer IUE resolution)

		N_{TOT}
N (Si II) = few x 10^{14} cm^{-2}		10^{19} cm^{-2}
N (C IV) = $10^{14} cm^{-2}$		few x 10^{17} cm^{-2}

The average density of material over the whole 50 kpc line of sight ($T \leq 10^5$ °K) is approximately 10^{-4} cm^{-3}.

<u>c. Summary</u> We can summarize the observations as showing that there does exist cold gas in ($T \leq 10^5$ °K) in the halo of our galaxy, probably in the form of discrete clouds with a range of ionization states. The average density of this gas is around 10^{-4} cm^{-3}. There is no direct evidence for hotter halo gas ($T \gtrsim 10^5$ °K) which would provide the confinement of these clouds in the Spitzer model. This hot gas has densities of less than 10^{-3} cm^{-3}.

<u>III. Formation of Hot Gaseous Winds in Elliptical Galaxies</u> As discussed in the introduction it has been suggested on theoretical grounds that gas is stripped from elliptical and SO galaxies by the formation of hot winds powered by the dynamical energy input of supernovae within the galaxy.

Bregman (1978) has made the most extensive studies using a 2-D numerical code to simulate the flow from galaxies with varying bulge to disk ratios. The criterion for formation of an outflowing wind can be stated in terms of two energy requirements.

<u>(1) Sufficient Energy Input</u> Define $T_o \equiv T_*$ (temperature corresponding to stellar motions) + T_{SN} (additional energy input from SN or other sources) we require the approximate condition $\frac{3k_BT_o}{m_p} > -\Phi$ or $T_o > T_{crit}$ where k_B is the Boltzman constant, m_p the proton mass and where Φ is the binding potential of gas with respect to infinity at a given point.

For our own galaxy in the solar neighborhood we have $T_{crit} = 10^6$ K, while at the galactic center $T_{crit} = 3 \times 10^6$ K. For a typical elliptical center T_{crit} is around 5×10^6 K.

<u>(2) Radiative Energy Losses Must Be Unimportant</u> We also must require that the energy be retained and not radiated away. This will be the case if the cooling rate does not exceed the heating rate, or, alternatively, if the cooling time is long compared with the flow time from the galaxy. In a typical elliptical galaxy the mass ejection rates are very approximately,

$$\dot{M} = 0.015\ M_\odot/yr\ (10^9\ L_\odot)^{-1}$$

or

$$\dot{M} = 1/2\ M_\odot/yr \text{ for } L = 3 \times 10^{10}\ L_\odot$$

While the supernova rate may be around 1/(100 - 300 yrs) implying in energy injection at a rate 10^{41} - 3.10^{41} ergs/s. Here $T_* \approx 3.10^6$ °K and $T_o \gtrsim 10^7$ °K. Comparing with T_{crit}, suggests that <u>most ellipticals will</u>

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variation in T_{SN}.

Of course these are local criteria and the true criterion must really be averaged over the whole flow. In particular Bregman has emphasized the possibility of partial winds. In elliptical galaxies gas in the central regions may be gravitationally bound while the outer regions form an outflowing wind. It is probably this rather than radiative cooling of what would otherwise be a stable wind which gives rise to cold emitting gas at the centers of about 15 to 20% of the elliptical galaxies which show optical emission lines.

IV. Haloes and Winds in Our Own Galaxy Theoretical studies of the formation of a hot gas halo or wind in our own galaxy have been given by various authors. McKee and Ostriker (1977) and Cox (1978) have considered the possibility of a galactic wind powered by halo supernovae, while Shapiro and Field (1976) have considered the possibility that hot gas in the disk of the galaxy flows out, radiatively cools, and falls back into the disk. General models have recently been extensively considered by Chevalier and Oegerle (1979).

We may first note that the presence of hot gas in the disk implies a substantial mass outflow into the halo, since this gas is gravitationally unbound. If the filling factor (β) of the hot gas is large, material freely streams out and the mass flow rate is

$$\dot{M} = 8\ \beta\ P_{-12.3}\ T_6^{-1/2}\ R_{15}^2\ M_\odot/yr$$

while if the filling factor is small pockets of hot gas (scalesize ℓ) buoy out of the galaxy and the mass flow is reduced to

$$\dot{M} = 0.2\ \{\frac{\beta}{0.2}\}\ \underline{P}_{-12.3}\ R_{15}^2\ \{\frac{\ell}{H_c}\}^{1/2}\ M_\odot/yr$$

Here, $\underline{P}_{-12.3}$ is the gas pressure in disk in units of $10^{-12.3}$ ergs cm^{-3}

R_{15} - galactic radius in units of 15 kpc

T_6 - gas temperature in units of 10^6 K

β - filling factor of hot gas

ℓ/H_c - ratio of cavity size to disk cold gas scaleheight.

This mass flow may form a wind, a halo or a fountain depending on the rate of energy injection into the halo and the energy which it carries from the disk. The condition for the gas to cool in the halo may be written in terms of the global energy inputs and losses as

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$$\dot{E}_R > \dot{E}_M + \dot{E}_H$$

$\dot{E}_R$ - total radiative energy losses through halo;

$\dot{E}_M$ - energy with which mass enters;

$\dot{E}_H$ - halo energy input.

The results are summarized in figure 1 (redrawn from Chevalier and Oegerle)

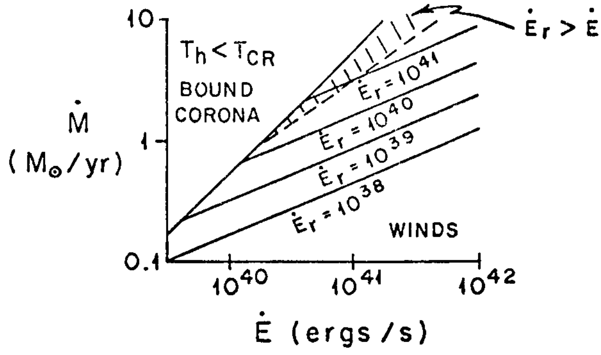

FIG. 1

in terms of the mass input and the total energy input. The first line shows the condition for a wind to form and the dashed region the condition that the integrated radiative energy losses be important. This is a relatively small region of the parameter space, but could be applicable to high mass flows. Since the halo energy injection rate is probably around a few times 10^{41} ergs/s from halo SN (McKee and Ostriker 1977) it is likely, as McKee and Ostriker and Cox have suggested, that an unbound wind forms. Typical temperatures and densities will be around 10^{-3} cm^{-3} with temperatures of few times 10^6 °K and the results are just consistent with the soft X-ray observations.

(5) Future Observations In the immediate future the advent of improved detectors will allow high resolution spectroscopy (~ 10 km/s or less) on many extragalactic sources including the brighter quasars. This will provide many lines of sight and allow us to derive distributions and densities for the cold gas in the haloes of our own and other galaxies. With the space telescope's UV capability we can investigate the ionization structure and abundances in this gas and with the NV absorption line constrain the amount of intermediate temperature material much more strongly. Finally the next generation of X-ray instrumentation may provide us with spectrometers capable of directly detecting halo gas in the soft X-ray absorption lines. (This requires an order of magnitude increase in effective area over the present Einstein spectrometers). (There are a number of useful X-ray lines which may be used to sample the halo gas at various temperatures from N VI (log T ~ $10^{5.6}$) though to Fe XXII (log T = $10^{7.5}$)). Ultimately this is the technique which will allow us to derive density and temperature profiles in the hot halo gas.

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