INFLOW OF NEUTRAL GAS TOWARD THE GALACTIC DISK

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Summary: I highlight the evidence for inflow of neutral gas toward the disk of the Galaxy. The Milky Way is accreting 0.2–0.5 $M_\odot$/yr of extragalactic atomic hydrogen at very high velocities. The interaction of infalling clouds with galactic material produces large-scale disturbances in the interstellar medium. Although the injection of energy into the galactic disk by infalling neutral gas is only 1% of the energy from supernovae, the impinging of high velocity neutral gas may be a relatively important source of energy in localized regions of the outer Galaxy.

In the solar neighborhood the downfall rate of HI at intermediate velocities is 2.72×10^{-8} $z(\mathrm{kpc})^{-1}$ $M_\odot$ pc^{-2} yr^{-1}, which if representative of the whole galactic disk, is at least 10 times more massive than the estimated accretion rate of extragalactic HI at very high velocities. This implies that most of the neutral gas that is infalling in the solar vicinity has originated in the galactic disk. It is concluded that in the Milky Way galaxy there is a moderate inflow of extragalactic neutral gas on top of a more intensive disk-halo circulation.

I. INTRODUCTION

The infall of gas toward the galactic disk is of outmost importance for our understanding of the structure and dynamics of the interstellar medium, and here I concentrate in the following questions: Is there an inflow of neutral gas toward the Galaxy?. What is the mass inflow rate?. What is the energy injected into the disk by infall of high velocity neutral gas and how it compares with other sources of energy?. What is the downfall rate of HI at intermediate velocities in the solar neighborhood, and how it compares with the accretion of neutral gas at very high velocities?

The studies on high velocity clouds of neutral hydrogen (HVC's) could provide clues to answer these questions. However, as pointed out by several authors (see the review by van Woerden, Schwarz, and Hulsbosch 1985, and references therein) the distance to these objects is unknown. Furthermore, it is not known how the dynamics of the system of high velocity clouds are related to the rotation of the galactic disk.

Despite these difficulties there are several indications that a subsample of HVC's is of extragalactic origin. Mathewson, Cleary , and Murray (1974) discovered a complex of clouds (Magellanic Stream) that extends more than 180° in the sky and is physically connected to the Magellanic galaxies. Besides, in the galactic anticenter there is a complex of clouds approaching the Milky Way with very high velocities (VHVC's; [V]>140 km/s). This gas must be extragalactic, since using current mass models for the Galaxy (e.g.: Clutton-Brock, Innanen, and Papp, 1977; Rohlfs and Kreitschmann, 1981), I find that for these clouds to be accelerated to their extreme galactocentric velocities of 250 km/s, they should have started their descent from distances greater than 30 kpc from the galactic plane. At last, there is a galactic hemispheric asymmetry in the distribution of VHVC's, since most VHVC's are in the Southern Hemisphere. Giovanelli (1981) has argued that this asymmetry invalidates the possibility of a galactic fountain origin for most of the VHVC's.

II. HIGH VELOCITY INFLOW OF NEUTRAL GAS.

Because the line-of-sight component of the solar motion in the galactic center and anticenter directions is small, surveys in these two regions of the sky offer favorable conditions for the detection and unbaised study of gas with high anomalous motions. In the galactic anticenter, Hulsbosch and Wakker (1988, and references therein) find a population of clouds having negative velocities, up to -250 km/s with respect to the galactic standard of rest. In Figure 1a I plotted the distribution of clouds with [V}>140 km/s using data from Hulsbosch and Wakker (1988). More than 99% of the column density of the VHVC's in this region of the sky has negative velocities.
Figure 1b shows the distribution of clouds in the opposite direction of the sky, namely, in the inner Galaxy, using the results of Mirabel and Morras (1984) complemented by data recently reported by Hulsbosch and Wakker (1988) and Bajaja et al. (1985).

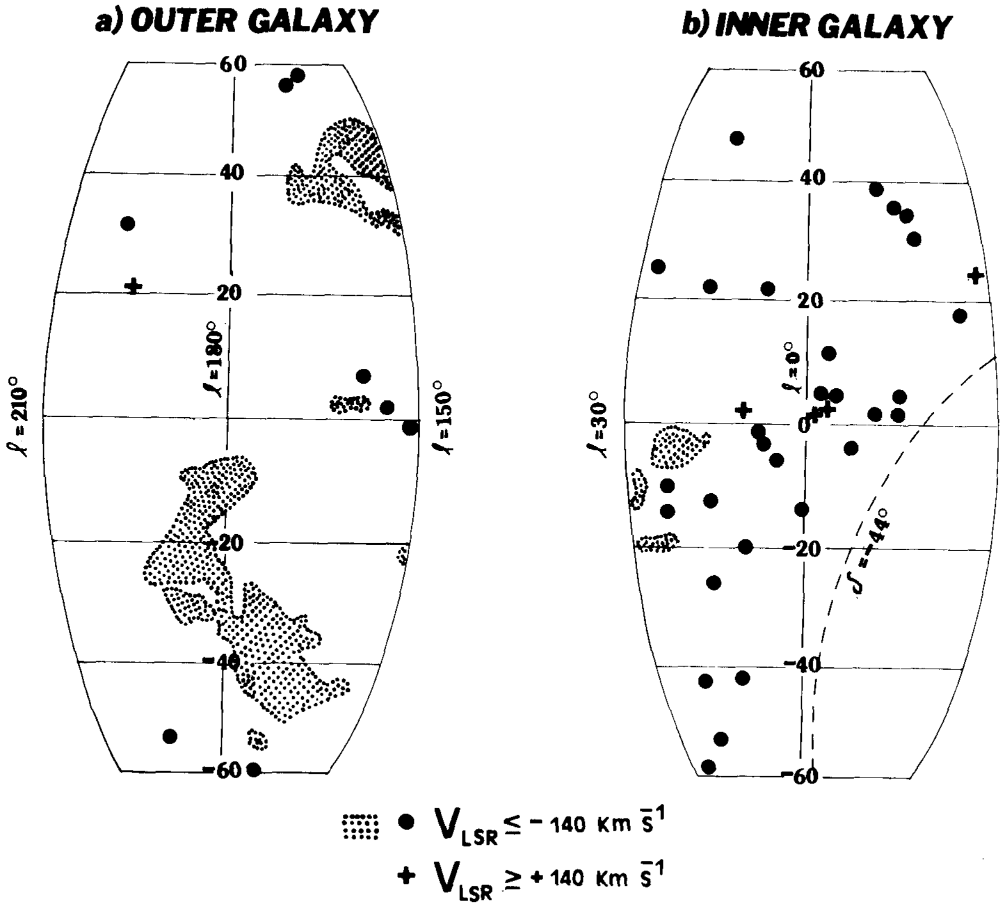

Figure 1: Distribution of atomic hydrogen with very high velocities in the outer and inner Galaxy. The preponderance of inward motions in these two regions of the sky is the best evidence for a high velocity inflow of gas toward the Milky Way. Data are from Mirabel and Morras (1984), Bajaja et al. (1985), and Hulsbosch and Wakker (1988).

The region south of declination -44°, the southern limit of the survey conducted from Green Bank by Mirabel and Morras (1984), was surveyed by Bajaja et al. (1985) using a less sensitive receiver system. Figure 1b shows that in the inner Galaxy there is also a clear preponderance of individual clouds (84%) and overall column densities (95%) having very high negative velocities.

The striking preponderance of clouds with the same extreme inward motions in the center and anticenter regions of the sky shown in Figure 1, is the strongest evidence for a high velocity inflow of neutral gas toward the Galaxy. In the most simple infall scenario it is likely that the clouds will move preferencially toward the central regions of the Galaxy. Hence, for an observer in the solar system, most of the infalling gas in the anticenter should have radial motions toward the observer. In the direction of the inner galaxy, there must be a preponderance of clouds with negative velocities. However, some infalling objects located between the Sun and the galactic center will be receeding from the observer. This is what shows Figure 1 where 99% of the gas with very high velocities in the anticenter has negative velocities, whereas in the inner galaxy about 5% of the gas is detected at positive radial velocities.

In the context of the inflow hypothesis, most clouds with very high negative velocities observed in the direction of the inner Galaxy are likely to be at distances greater than 10 kpc from the Sun, beyond the galactic center. Hence, for a given physical size, the clouds detected in the inner Galaxy should appear smaller than their counterparts in the anticenter. Maps of several clouds carried out by Mirabel and Morras (1984) confirm this prediction, since clouds with high negative velocities in the inner Galaxy typically have angular sizes that are about 5 times smaller than their counterparts in the anticenter.

The computation of the net influx of gas toward the Milky Way depends on several unknown factors, such as the distance to the clouds, the motion of the objects in the plane of the sky, and the actual distribution of infalling gas over the whole sky. To estimate the influx of neutral gas toward the Galaxy I have used the results summarized in Figure 1. In other words, I have used data from the 30% of the sky that offer the most favorable conditions for an unbiased detection of neutral gas with truly large anomalous motions ([V]>140 km/s).

The HI with $V_{lsr} < -140$ km/s in the 7200 squares degrees of the anticenter shown in Figure 1a has a mass $M(HI) = 2.63 \times 10^4 D^2 (kpc) M_\odot$, after correcting for the partial sky coverage of the survey by Hulsbosch and Wakker (1988). From the search by Kulkarni and Mathieu (1986) for interstellar optical absorption lines in the clouds of the anticenter we can assume that the very high velocity gas in this region is at distances greater than 2 kpc from the Sun. An upper distance of 10 kpc seems reasonable, given the galactocentric velocities reached by the infalling gas. Hence, assuming that the gas is at a mean distance of 6 kpc from the Sun, and that it is moving toward the inner Galaxy with a space velocity of 250 km/s, I obtain an infall rate of 0.03 $M_\odot$/yr for the anticenter, which extrapolated to the whole sky implies 0.18 $M_\odot$/yr.

The HI with V_{lsr} <-140 km/s in the direction of the inner Galaxy that is shown in Figure 1b has a mass M(HI) = 7.23 x 10^3 D^2(kpc) $M_\odot$, after correcting for the partial sky coverage of the surveys. Using the current mass models for the Galaxy, I infer that the clouds with such high infall velocities shoud be located beyond the galactic center at distances from the Sun of 10-30 kpc. Assuming that the VHVC's are at a mean distance of 20 kpc from the Sun, and a space velocity toward the galactic center region of 250 km/s, I obtain an infall rate of 0.04 $M_\odot$/yr in that region, which extrapolated to the whole sky implies 0.22 $M_\odot$/yr.

The results from VHVC's can be summarized as follow: from unbiased surveys that cover 30% of the sky we conclude that 0.20 $M_\odot$/yr of neutral gas is being acreeted by the Milky Way at very high velocities.

III. HVC's-MILKY WAY INTERACTIONS: A "SPLATTER" IN THE OUTER GALAXY.

A natural consequence of the high velocity infall of neutral gas must be the interaction with the interstellar gas of the Milky Way. Oort (1970) proposed that most high velocity streams of HI clouds with more moderate velocities ([V_{lsr}]<140 km/s) are galactic clouds which have been set in motion by gas of extragalactic origin that has penetrated into the galactic halo. However, no direct observational evidence for the physical interaction between extragalactic VHVCs and galactic material had been found until recently.

Mirabel (1982) and Kulkarni, Dickey and Heiles (1985) found evidences for such an interaction in the anticenter region of the sky. Figure 2 shows the tip of the anticenter complex of very high velocity clouds together with a remarkable supershell of HI at V = - 71 km/s identified by Heiles (1984). Kulkarni, Dickey and Heiles (1985) find that this supershell consists of post-shock gas that is cooling down. They give several reasons to interpret this supershell as the result of a "cosmic

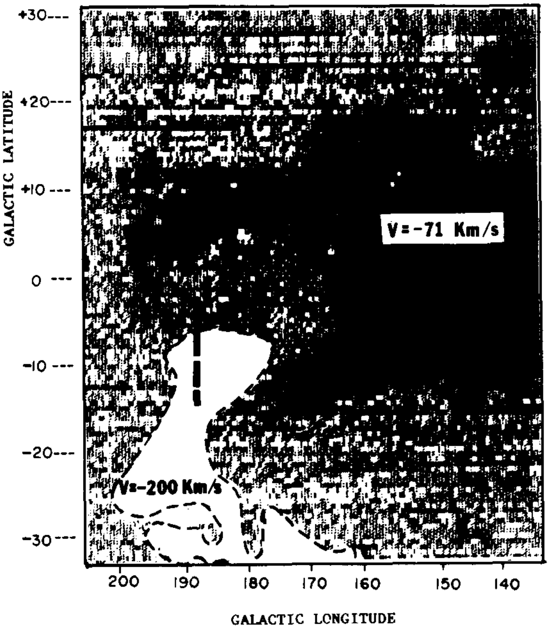

Figure 2: Colliding very high velocity cloud ACI (v = - 200 km/s) represented in white, superimposed on a grey-scale representation of the "anticenter shell" centered at v = -71 km/s (Heiles, 1984). The broken lines represent the extent of the position-velocity map at the edge of ACI that is presented in Figure 3.

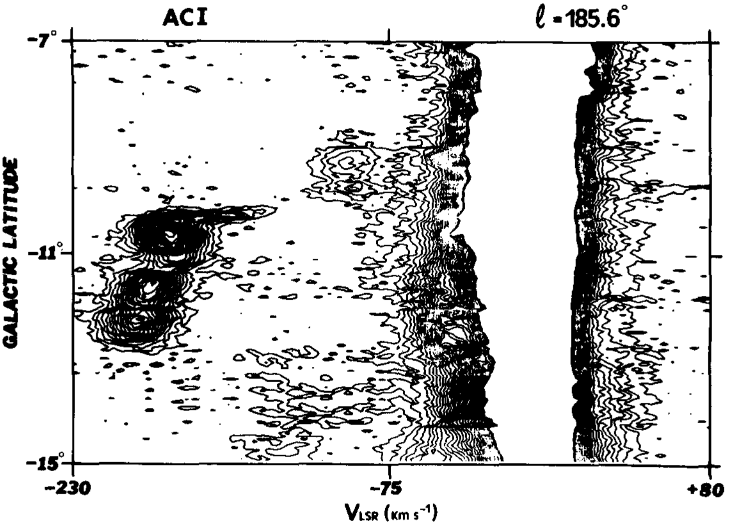

Figure 3: High resolution position-velocity map by Morras and Mirabel (1989) along the broken lines shown in Figure 2. The interaction of ACI with the Milky Way is revealed by the steep edge and decceleration of the very high velocity cloud at the same positions where are found kinematic disturbances spanning over 200 km/s.

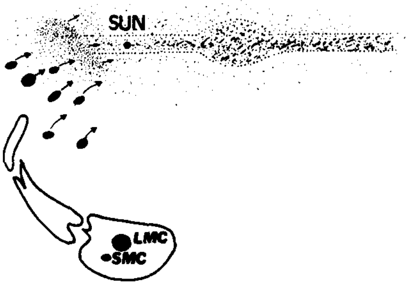

Figure 4: Sketch of the model proposed by Mirabel (1981) for the impinging stream of very high velocity clouds producing the "galactic splatter" in the anticenter of the Galaxy.

splatter" produced by impinging HVC's, rather than by supernovae explosions.

The complementary distribution on the sky between the gas at -200 km/s and the gas at -71 km/s shown in Figure 2, supports that hipothesis. This type of distribution is expected as a result of an interaction, since at the position where the extragalactic clouds have been slowed down, the galactic halo gas has already been accelerated to -71 km/s. At greater distances, where the gas infalling with - 200 km/s has not yet reached the Milky Way gas, no prominent features at -71 km/s have been produced.

The anticenter complex of very high velocity clouds extends more than 50° in the southern galactic sky, but strikingly, it does not "cross" toward the northern hemisphere, suggesting a break in the motion of the -200 km/s stream at its closer angular distance from the galactic disk. Using the Arecibo telescope, Mirabel (1982) studied the region where the VHV gas breaks down, and found direct evidence for the physical connection of gas with velocities in the range of - 200 km/s to + 20 km/s. Figure 3 shows a high sensitivity, position-velocity map by Morras and Mirabel (1989) along the broken line in Figure 2, which cuts the northern edge of the very high velocity cloud ACI. The jump in velocity and the "shock" structure at the edge of the ACI, occur at the same position of disturbances observed in the gas with lower velocities, and this argues for an interaction with high-z galactic material.

IV. THE INFLOW OF MASS AND THE ENERGY BUDGET IN THE GALACTIC DISK.

Mirabel (1981, 1982) has proposed that the anticenter complex of VHVC's is a fragment of the Magellanic Stream that is impinging into the Milky Way. As sketched in Figure 4, the northern clouds of the anticenter complex are falling obliquely toward the galactic disk, and have already reached the high-z gas of the Milky Way, producing the "galactic splatter" studied by Kulkarni, Dickey and Heiles (1985).

The remarkable anticenter shell noted by Heiles (1984) has an energy of 10^{53} erg (Kulkarni, Dickey, and Heiles 1985), which is difficult to explain on the basis of supernovae explosions. On the contrary, this energy is comparable to the kinetic energy of the VHVC's in that region of the sky. If the VHVC "ACI" in Figures 2 and 3 is at distance of 5 kpc from the Sun (Kulkarni and Mathieu, 1986), its mass would be 4×10^{5} $M_{\odot}$, with a kinetic energy of 2.5×10^{53} erg, enough to produce the most energetic HI supershells found by Heiles (1984).

The Magellanic Stream has a total mass of 2.8×10^{5} D^{2} (kpc) including the HI corona in which the Magellanic galaxies are embedded. The long streamer with negative velocities that is approaching the Milky Way has one third of the column density of the whole Magellanic Stream (Mathewson, Cleary and Murray, 1974), and assuming that it is at a mean distance of 40 kpc, one finds 1.5×10^{8} $M_{\odot}$ for the northern streamer. The ballistic downfall of the northern streamer from a distance of 40 kpc will take 3×10^{8} years, producing a mass inflow of 0.5 $M_{\odot}$/yr. This is comparabable with the present infall rate infered from the VHVCs found in the region of the sky shown in Figure 1.

Taking the Galaxy as a whole, the energy injected by HVC's will be about 2×10^{47} erg/yr, only 1% the energy contributed by supernovae of 10^{51} erg exploding at a rate of 1/50 yr^{-1}. However, outside the solar circle, the energy due to the infall rate of neutral gas may be relatively important, since the supernovae rate decreases with galactocentric distance. As Heiles (1989) stated, comparativelly few molecular gas and massive stars populate the outer regions of the Galaxy, and in that region, supernovae explosions may not dominate completely the energy balance of the interstellar medium. It remains an open question if the downfall energy of HVC's dominates over supernovae in the outskirts of the Galaxy.

Franco et al. (1988) followed Tenorio-Tagle's (1980) idea and propose a model in which the molecular cloud complexes in Orion and Monoceros are the result of interaction of HVC's with Milky Way material. In their model, cloud-galaxy collisions are able to generate massive shocked layers and self-gravity can then provide the conditions for the transformation of these layers into molecular clouds.

Ostriker has pointed out at several meetings that if the gas is stopped abruptly when hitting the disk, this energy would have to be radiated in the x-rays, violating the observed background. The temperatures of the collisionally heated gas would be in the range of 10^6-10^7 K for velocities in the range of 100-300 km/s, which would correspond to radiation in the range of 0.25-2.5 kev. In this respect, I wish to point out the following: the decceleration in the upper halo of clouds with densities smaller than 0.1 HI cm^{-3} must be gradual, and the kinetic energy converted into thermal energy would be radiated in the soft x-rays as the clouds cool down. The mean free path for photons radiated by a plasma of 5 x 10^5 K is 10^{19} HI/cm^{-2} (Bloch et al. 1986), implying that they must be completely absorbed after travelling 3 pc inside a typical HI cloud of the disk with a density of 1 HI atom cm^{-3}. The anticenter complex of HVC's is likely to be at distances 3 orders of magnitude larger than the mean free path of the soft x-rays, and therefore, there is no chance for detecting the collisionally ionized gas. Furthermore, Stern and Bowyer (1979) find a high latitude excess in the 0.1 kev flux whose origin is still unclear. This plasma could partially be due to gas heated as a result of the downfall of neutral gas.

V. DOWNFALL OF ATOMIC HYDROGEN IN THE SOLAR NEIGHBORHOOD.

The galactic polar caps offer favorable conditions for the study of motions perpendicular to the galactic plane. 25 years ago, Dieter (1964) proposed that a large fraction of the HI detected at high latitudes could be condensations descending from the halo. The downflow of atomic hydrogen in the solar neighborhood was clearly established by the work of Wesselius and Fejes (1973) and Weaver (1974). The best illustration of the downfall phenomenon has been presented in Figure 9 of Weaver (1974). Despite the large amounts of observations, to my knowledge, there has been no quantitative estimation of the mass infall rate.

To make a quantitative estimate of the inflow of neutral gas in the solar neighborhood, Mirabel and Morras (1989) have recently used the 21 cm survey by Stark et al. (1983), which was conducted with the horn antenna at Crawdford Hill. We find a clear asymmetry in the high velocity wings of the gas in the galactic polar caps: the negative velocity wings extend to higher velocities than the positive velocity wings in the majority of the directions. This phenomenon is

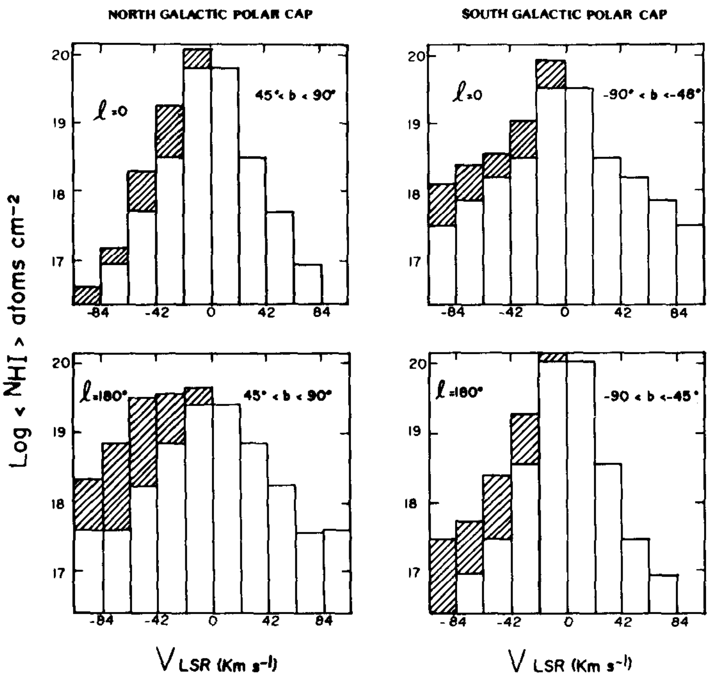

Figure 5: Histograms for $l = 180^{\circ}$ and $l = 0^{\circ}$ of the HI column densities in the galactic polar caps. The excess of blueshifted HI relative to the redshifted HI is indicated by hatched areas. The column densities were derived by Mirabel and Morras (1989) from the 21 cm survey by Stark et al. (1983).

particularly striking in the directions of $l = 180^{\circ}$ and $l = 0^{\circ}$, where no effects due to the solar motion about the galactic center are expected.

Figure 5 shows histograms of the mean column density $\langle N_{HI} \rangle$ in the galactic polar caps for $l = 180^{\circ}$ and $l = 0^{\circ}$, computed from the averages of the individual profiles, in intervals of 21 km/s (4 channels). The histograms in Figure 5 show a clear asymmetry with considerable more blueshifted gas than redshifted. The excesses of blueshifted column densities relative to the redshifted ones are indicated in the histograms by the hatched areas.

Kulkarni and Fich (1985) have shown that a large fraction of the HI in any direction of the sky is fast moving, with large positive and negative velocities. Therefore, to estimate the actual mass infall rate of atomic hydrogen in the solar neighborhood we use only the excesses in column densities of the blueshifted gas relative to the redshifted gas. We have taken the excesses in the polar caps for $l = 0^\circ$, 90°, 180° and 270°. The mass infall rates were computed with the equation:

$$\dot{M} = 8.1 \times 10^{-12} \sum \langle N_{HI} \rangle_i \, (10^{18}\ \mathrm{HI/cm^2})\ V_i\,(\mathrm{km/s})\ z_i^{-1}\,(\mathrm{kpc})$$

where $\dot{M}$ is in $M_\odot\ pc^{-2}\ yr^{-1}$. We find $\dot{M} = 2.72 \times 10^{-8}\ z(kpc)^{-1}\ M_\odot\ pc^{-2}\ yr^{-1}$, where z is the height of the infalling gas above the galactic plane. The gas with $0 > V > -21$ km/s contributes 30% of the total amount, and the downfall from the Northern Hemisphere is 60% of the total inflow.

If the solar neighborhood were representative of an area of the galactic disk of total radius r(kpc), the infall rate would be $\dot{M} = 8.6 \times 10^{-2}\ r^2(kpc)\ z^{-1}(kpc)\ M_\odot\ yr^{-1}$. For z = 3 kpc (Kahn, 1989) and r = 10 kpc, we obtain $\dot{M} = 3\ M_\odot\ yr^{-1}$, comparable to the output rates of matter toward the halo due to supernovae (Heiles, 1989). This infall rate is about one order of magnitude higher than the infall rate from VHVC's. It is interesting that the mechanical momentum of the VHVC's is about the same as the mechanical momentum of the infalling gas at intermediate velocities.

Since the infall rate at intermediate velocities in the solar neighborhood is more than 10 times higher than the accretion rate of extragalactic neutral gas at very high velocities, most of the infalling matter in the solar vicinity must have originated in the disk, implying an active circulation flow of gas from the disk to the halo, and from the halo to the disk.

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