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TURBULENCE IN THE OUTSKIRTS OF THE MILKY WAY

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ABSTRACT

In external galaxies, the velocity dispersion of the atomic hydrogen gas shows a remarkably flat distribution with the galactocentric radius. This has been a long-standing puzzle because if the gas velocity dispersion is due to turbulence caused by supernova explosions, it should decline with radius. After a discussion on the role of spiral arms and ram pressure in driving interstellar turbulence in the outer parts of galactic disks, we argue that the constant bombardment by tiny high-velocity halo clouds can be a significant source of random motions in the outer disk gas. Recent observations of the flaring of H I in the Galaxy are difficult to explain if the dark halo is nearly spherical as the survival of the streams of tidal debris of Sagittarius dwarf spheroidal galaxy suggests. The radial enhancement of the gas velocity dispersion (at $R > 25$ kpc) due to accretion of cloudy gas might naturally explain the observed flaring in the Milky Way. Other motivations and implications of this scenario have been highlighted.

Key words : galaxies: intergalactic medium—galaxies: ISM—ISM: kinematics and dynamics—ISM: structure—turbulence

I. INTRODUCTION

Many physical processes may contribute to driving turbulence in the interstellar medium (ISM) of galactic disks: stellar winds, expanding H II regions, clustered and field supernova explosions, hydrodynamic or magnetohydrodynamic instabilities, frequent minor mergers of small satellite clumps, shocks from spiral density waves, differential rotation, ram pressure or infalling gas clouds and streams (see Mac Low & Klessen 2004 for a review). Studies of the second-moment (or velocity dispersion) of H I emission lines may provide relevant information about what mechanism is more important at different galactic radii. Although the one-dimensional velocity dispersion of H I gas, σ, is difficult to measure observationally, there is now solid evidence that, in most spiral galaxies, σ vary radially from $\sim$ 12–15 km s^{-1} in the central parts to a very constant value 6–8 km s^{-1} over several scale lengths along the extended outer parts (Dib et al. 2006, and references therein). The observed correlation between star formation rate and the H I velocity dispersion in the optical disk indicates that the stellar activity, mainly through supernova explosions, is the main mechanism to drive turbulence within the optical radius. If turbulence is driven by supernova, Dib, Bell & Burkert (2006) found that the velocity dispersion is expected to be constant beyond a radius, R_t, where the supernova rate is one half the Galactic value at 15.5 kpc (quiescent regime). Within R_t, the velocity dispersion increases rapidly when increasing supernova rate, mimicking the "starburst regime". However, the predicted velocity dispersion $\sim$ 3 km s^{-1} of the H I gas in the quiescent regime is a factor $\sim$ 2 smaller than the observed values. This leads to conclude that either there are other physical processes driving turbulence or the supernova feedback efficiency has been underestimated.

The constancy of the H I velocity dispersion in the outer parts, i.e. beyond the optical disk, might have a natural explanation if the H I gas layer is heated by metagalactic UV radiation to a constant temperature of 8,000 K (Schaye 2004). However, since the gas is gravitationally stable in the outer disks, the observed low level of star formation is very difficult to explain in the absence of stellar compression and turbulence compression (e.g., Ferguson et al. 1998). The double exponential radial profile of the star formation rate recently observed in spiral and dwarf irregular galaxies has been also interpreted as a consequence of the turbulent nature of the gas in the outer disks (Elmegreen & Hunter 2006). Other reasons to believe that the H I disk is turbulent at any radius can be found in Sánchez-Salcedo et al. (2007).

Due to their low surface density, the outskirts of disks are very responsive to external perturbations. Their interaction with the intergalactic medium through ram pressure and cold gas accretion may be important to understand the morphology and dynamics of H I gas. In this work, we consider the new All Sky Leiden-Argentine-Bonn (LAB) H I survey in an attempt

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Corresponding Author: F. J. Sánchez-salcedo to find out possible mechanisms responsible for driving turbulence in the outer Galaxy. The LAB survey has provided us a three-dimensional view of the H I disk of the Galaxy up to a distance of 40 kpc from the Galactic center with unprecedented coverage both spatially and kinematically (Kalberla et al. 2005). This kind of information is impossible to obtain in any other external galaxy.

II. DRIVING TURBULENCE IN THE OUTER PARTS OF GALAXIES

As already said, if turbulence is driven by the energy injected by supernova explosions, the predicted velocity dispersion would be a factor ~ 2 smaller than the observed values (Dib et al. 2006). It is important to know to what extent the gas random motions in the outer disk are the result of other driving mechanisms such as large-scale non-axisymmetric perturbations, ram pressure from the intergalactic medium or supersonic accretion of cold gas.

The outer parts of the Milky Way are not axisymmetric. The first indications of the existence of spiral arms up to 30 kpc from the Galactic center by Henderson et al. (1982) have been confirmed by Levine et al. (2006b). The response of the gas to a spiral gravitational perturbation is complex because it develops a combination of a shock and a hydraulic jump, with subsequent vertical bouncing (Martos & Cox 1998; Gómez & Cox 2002). When the gas entries to the arm, it moves up ahead of the stellar arm, speed up over it, and fall behind with large bulk velocity. Other different processes combine to generate small-scale structure and turbulence (e.g., Kim et al. 2006). If so, one would expect an enhancement of the gas vertical velocity dispersion in the spiral arms. However, Petric & Rupen (2007) find no correlation between locations of enhanced velocity dispersion and the spiral arms in the spiral galaxy NGC 1058. On the contrary, regions with high velocity dispersion try to avoid the loccus of the spiral arm. It seems likely that the arms beyond the corotation radius, which are thought to be excited by tidal interactions, are rather weak and only generate a vertical jump of the order of the thickness of the disk $\sim h$. If this is the case, the postshock gas achieves hydrostatic equilibrium very soon (after a few vertical crossing times, $\sim h/c_s$ with $c_s \approx 9$ km s^{-1}) and the evolution is close to previous two-dimensional simulations by Tubbs (1980) and Soukup & Yuan (1981), who found that largest downflow was due to the preshock gas readjusting its vertical structure as it flows into the interarm potential. In the case of the Galactic outer arms, the extraordinary anticorrelation between the thickness of the disk and the H I surface density (Levine et al. 2006b) may be interpreted as evidence of vertical near-hydrostatics as in Tubbs (1980) and Soukup & Yuan (1981). It seems, therefore, unlikely that spiral arms are able to maintain the homogeneous level of turbulence in the outer disk.

The comet-like appearance of the integrated H I map of the dwarf irregular galaxy HoII led to suggest that this galaxy is affected by ram pressure from an intragroup diffuse-gas medium (Bureau & Carignan 2002). They point out that ram pressure may have the capacity to enlarge preexisting holes where no star formation is expected or observed. The Local Group dwarf galaxy Pegasus (DDO 216) also displays a cometary appearance (McConnachie et al. 2007). The density of the medium required to ram pressure strip Pegasus is 10^{-5} to 10^{-6} cm^{-3}. The question that arises is: can the ram pressure mixing generate enough turbulence to account for the observed values in the outer disk of galaxies? We think that it is unlikely that ram pressure can drive H I turbulence along a very extend radial range because its effects depend strongly on the surface density. For our Galaxy, Levine et al. (2006a) derive the best fit for the H I surface density beyond 14 kpc to be:

$$\Sigma_{\rm HI}(R) = 4.5 \exp\left[-(R - 14\,{\rm kpc})/4.3\,{\rm kpc}\right] {\rm M_\odot pc^{-2}}. \tag{1}$$

Thus, the H I surface density decays a factor 340 from the optical radius at $R = 15$ kpc to the last H I measured point (at 40 kpc). Hence turbulent ram pressure mixing may be efficient only in a thin rim at the outer edge of the H I layer.

Sánchez-Salcedo et al. (2007) and Santillán et al. (2007) have explored an alternative scenario where the accretion of cold gas is responsible for driving turbulence. We will discuss the motivation and some implications of this model in the following sections.

III. ACCRETION OF GAS AND HIGH VELOCITY CLOUDS

Nowdays, there is no doubt that galaxies cannot be treated as isolated systems because are in a continuous process of accretion of both dark and baryonic material. The most powerful indirect evidence is the range of stellar ages and metallicities in galaxies like the Milky Way (Beckman et al. 2003). In particular, the so-called 'G-dwarf problem', or the diagrams of Be and Li versus Fe in the local disk stars are both solved in infall models with a constant inflow.

However, the question of how do galaxies get their gas remains open. Evidence for the accretion of material has grown over the past many years. The most spectacular interaction phenomenon is the Magellanic H I stream. The derived gas accretion rate of diffuse gas towards the inner Galactic halo due to the Magellanic stream was estimated to be $\sim 0.4\,{\rm M_\odot\,yr^{-1}}$. Much of the diffuse gas will become mixed with the hot gas but fragments of the interaction may reach the H I disk. The high-velocity clouds (HVCs) have been interpreted as clear evidence of cold gas accretion onto the disk. Brüns et al. (2001) found that some fraction of HVCs present a head-tail morphology probably as the result of interaction with a diffuse ambient medium. This observation would indicate that at least a fraction of the

HVCs are located in the Galactic halo. Westmeier et al. (2007) have observed the Andromeda galaxy to infer the nature of HVCs from their projected distances and find that it contains a population of HVCs close to the disk (distances ≤ 50 kpc). The non-detection of HVCs in six loose groups of galaxies, similar to the Local Group, by Pisano et al. (2007) implies that any tiny clouds are near to the galaxies and are not intragroup objects.

Metallicities have been measured for some HVCs and vary over a large range (Gibson et al. 2001), suggesting that they are not a homogeneous set. Although the nature of HVCs remains unclear, it seems likely that at least two models are required to explain the cloud distribution. In the following we discuss two possible scenarios for the formation of HVCs.

(a) HVCs from residual gas of galaxy formation

The gas accretion process has traditionally been thought to proceed via shock-heated halo gas cooling and falling into the disk (White & Rees 1978; White & Frenk 1991). Recently, the inclusion of the fragmentation as the hot gas cools and the formation of pressure supported warm clouds in the models has led to important predictions. For instance, Maller & Bullock (2004) predict, at any given time during the Milky Way recent evolution, several thousand condensed clouds with a total mass of the order of 2×10^{10} $M_\odot$.

Recent progress on the determination of distances to HVCs has allowed to address observational constraints on the HVC population around the Milky Way and groups of galaxies similar to our own Local Group (Pisano et al. 2004). Putman (2006) infer that the total mass in condensed infalling clouds is $\sim 6 \times 10^8$ $M_\odot$ if they are all at distances < 60 kpc. As discussed in Putman (2006), a hot halo with a baryonic mass of a few 10^{10} $M_\odot$ can fuel the Milky Way as this hot gas gradually cools and condense in clouds. If clouds fall in rapidly after they are formed, less clouds are visible in the halo at a given time. Thus, HVCs may still be a potential repository for large amounts of gas (see also Maloney & Putman 2003).

(b) HVCs in the Galactic fountain

A Galactic fountain is a possible mechanism to inject a large amount of hot gas from multiple supernovae into the lower galactic halo. Then the gas becomes thermally unstable and cools radiatively forming neutral HVCs (Oort 1970; Shapiro & Field 1976). Recently, Booth & Theuns (2007) perform numerical simulations of a galactic fountain in in a Milky Way-like galaxy. They demonstrate, through mock H I observations, that many of the observed features of the H I disk and its HVCs can be reproduced in this scenario. The simulated HVCs are found close to the Galactic disk, with a typical distance of 13 kpc from observers on the solar circle. These simulations show that the galactic fountain efficiently circles matter from the central parts of the galaxy to its outskirts. More precisely, when gas is launched at a radius $R_{\rm eject} < 8$ kpc, it falls back to the disk at a larger radius $\gtrsim 4 \times R_{\rm eject}$. The outer disk is being rained at a rate of around 0.5 $M_\odot$ yr^{-1}.

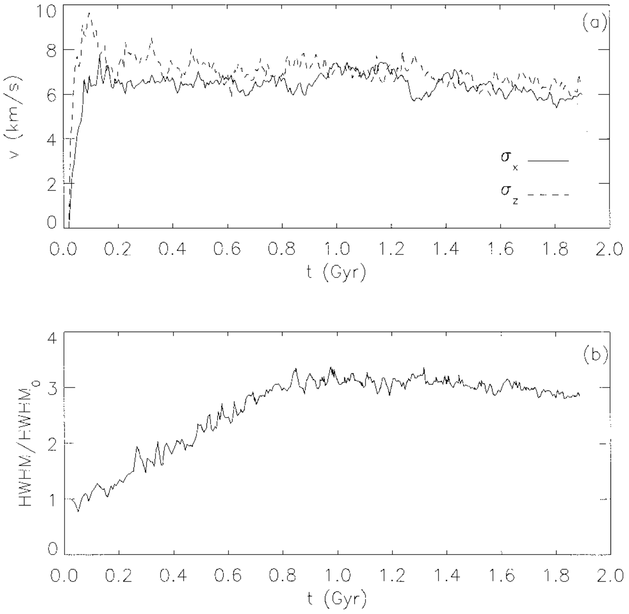

Fig. 1.— Temporal evolution of the velocity dispersion (panel a) and HWHM (panel b) of the H I layer in the 'standard' simulation of Santillán et al. (2007). The HWHM has been normalized to the initial value.

IV. FUELING TURBULENCE BY COLD GAS ACCRETION

Santillán et al. (2007) suggest that the rain of compact high velocity clouds on the disk not only can fuel the Milky Way with fresh material but can also be a potential source of random motions in outer H I disks. As discussed in the previous section, the outer disk may be rained on by Galactic fountain material driven by supernova explosions (Shapiro & Field 1976; Booth & Theuns 2007) or by inner starbursts (Benjamin & Shapiro 1993).

Falling HVCs and intermediate velocity clouds (IVCs) can perturb the disk in different ways. High-resolution two-dimensional magnetohydrodynamical simulations were carried out to quantify the effects of continuing infall of clumpy gas (HVCs and IVCs) in extended H I galactic disks. In order to illustrate the evolution of the disk, the velocity dispersion of the gas, σ_g, due to macroscopic random motions is shown in Fig. 1a for the standard isothermal simulation described in Santillán et al. (2007). Initially, the gas is in hydrostatic equilibrium, thus $\sigma_g = 0$. The clouds are injected from the top of the box at a height of 2 kpc and with a vertical velocity of 100 km s^{-1}. These clouds transfer momentum to the gas and the velocity dispersion increases up to a certain nearly constant value in a timescale of ~ 0.15 Gyr. Since the effective velocity dispersion increases, the disk becomes thicker in time (see Fig. 1b). In fact, in hydrostatic equilibrium,

$$\sigma_{\rm eff}^2 \frac{\partial \rho_g}{\partial z} = -\rho_g \frac{\partial \Phi}{\partial z}, \qquad (2)$$

with Φ the external and unresponsive gravitational potential, $\sigma_{\rm eff}$ the effective velocity dispersion of the gas $\sigma_{\rm eff}^2(t) = c_s^2 + \sigma_g^2 + v_A^2$, where c_s is the sound speed of the gas and v_A the Alvèn speed. For isothermal gas, Eq. (2) can be immediately integrated to obtain $\rho(z) = \rho_0 \exp(-[\Phi(z) - \Phi(0)]/\sigma_{\rm eff}^2)$ where $\rho_0(t)$ is the midplane volume density, which depends on time because of the accretion of mass. Assuming $\Phi(0) = 0$, the HWHM is the height z where $\Phi(z)/\sigma_{\rm eff}^2 = -\ln(0.5)$. Even though $\rho_0(t)$ increases in time, the thickness of the disk does not depend on ρ_0 but only on $\sigma_{\rm eff}$. From our ongoing discussion, it is clear that if hydrostatic equilibrium is a good approximation, the thickness should be constant once we reach a steady state, i.e. $\sigma_{\rm eff} \approx$const. In Fig. 1b we see that the HWHM of the disk, in fact, reaches a "steady-state" value but it takes ~ 0.8 Gyr, which is 5 times longer than the time to reach a constant turbulent velocity dispersion. Within the first 0.8 Gyr, the HWHM increases linearly with time. The discrepancy between these timescales is not the result of the breakdown of hydrostatic equilibrium, which is satisfied rather precisely; net deviations of the HWHM derived from hydrostatic equilibrium are less than 15%. The origin of this difference between timescales is that, in our standard simulation, $\sigma_{\rm eff}$ is an increasing function of time for the first 0.8 Gyr because v_A increases in time during this period. The reason is that, in our standard model, the magnetic pressure of the initial configuration increases with z. Therefore, falling clouds carry magnetic flux downwards and the magnetic field strenght grows in time in the disk until a new steady state magnetic configuration is reached.

For mass accretion rates consistent with current empirical and theoretical determinations, effective velocity dispersions in the warm phase of ~ 5–9 km s^{-1} are found, depending on the structural parameters of the clouds and injection velocity. Studies of the response of interstellar gas to falling clouds may constrain the maximum mass accretion rate in compact HVCs. The model of turbulence driven by cold gas accretion does not neccesarily implies that σ_g is constant with galactocentric radius. The exact radial variation of the H I line width depends on the uncertain contribution of the thermal broadening as a function of radius and on the adopted accreting mass flux $\dot{\Sigma}(R)$, which ultimately depends on what the origin of the condensing clouds is. In the following section we give a first attempt to constrain the model from the flaring of the H I Galactic layer.

V. THE GALACTIC H I FLARE

Traditionally, the observed thickness of the H I layer has been used to infer the shape of the halo assuming they follow a non-singular spheroid with flattening q:

$$\rho_{\rm dm}(R,z) = \rho_0 \left[\frac{R_c^2}{R_c^2 + R^2 + (z/q)^2}\right]^p. \qquad (3)$$

The method assumes that the gas is in hydrostatic equilibrium, the pressure tensor is round and isothermal with a constant velocity dispersion $\sigma = 9$ km s^{-1} in R and z, and ignores the contribution from non-thermal pressure as well as the ambient pressure or accretion flows. This method was applied to some external galaxies seen edge-on (Olling 1996; Becquaert & Combes 1997) and to our Galaxy (Olling & Merrifield 2000; Narayan et al. 2005). Olling & Merrifield (2000) conclude that significantly flattened halos are possible only in the case that the distance of the Sun from the Galactic center is smaller than ~ 7 kpc. Narayan et al. (2005) find that an isothermal halo ($p = 1$) described by a single constant q parameter does not match the observations if one considers a broad range of galactocentric distances. Using the new data of the LAB survey of the 21 cm line in our Galaxy, which led to precise measurement of the H I layer thickness up to radii of 40 kpc, Kalberla et al. (2007) achieve the same conclusion and require an isothermal spherical dark halo, plus a dark matter disk of mass 2–3 $\times 10^{11}$ M$_\odot$ or, alternatively, a highly prolate spheroid, to account for the global flaring of the Galactic H I disk. Even so, a marked depression in the derived flaring remains at distances 15 kpc $\lesssim R \lesssim 20$ kpc. To explain this, these authors suggest to add a massive dark ring at 13 kpc $< R <$ 18.5 kpc with mass 2.2 to 2.8 $\times 10^{10}$ M$_\odot$.

Here, we will proceed in a different way. We assume that the shape of the dark halo is measured with an entirely independent method and, hence, given the measured baryonic distribution of stars and gas and the shape of the dark halo, the flaring of the H I layer can be used to constrain the radial variation of the velocity dispersion of the gas.

The survival of streams of tidal debris apparently associated with the Sagittarius dwarf spheroidal galaxy (Sgr) against orbital precession require a rather spherical halo with a flattening in the range $0.9 < q < 1.1$ (Fellhauer et al. 2006, and references therein). Since this finding would compromise the credibility of the flaring technique which shows that a spherical halo is not able to explain the observed flaring curve, there is a lot of interest in explaining the flaring in a spherical dark halo.

In Fig. 2 we plot the azimuthally averaged flaring curve as derived from the LAB survey, assuming the IAU standard values ($R_\odot = 8.5$ kpc and $v_\odot = 220$ km s^{-1}), and the predicted scaleheight. For the translation of velocities to distances, the shape of the rotation curve was calculated self-consistently for a spher-

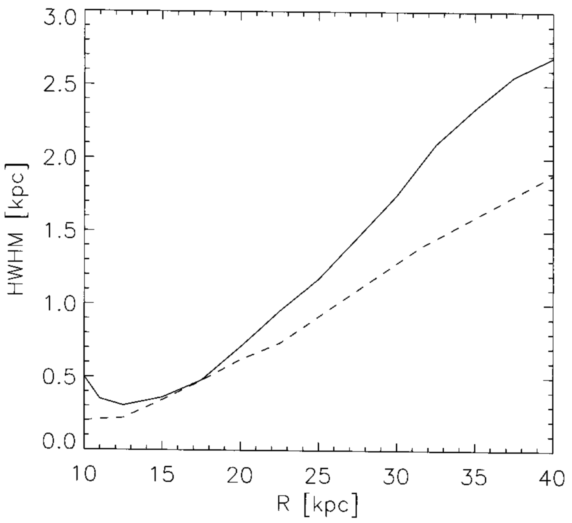

Fig. 2.— Observed (solid line) and predicted (dashed line) variations in the HWHM of the H I layer with radius. A spherical dark halo was assumed.

ical halo (Kalberla et al. 2007). The predicted H I flare was calculated combining the Poisson equation, $\nabla^2\Phi = 4\pi G(\rho_\star + \rho_g + \rho_{\rm dm})$, where $\rho_\star$ is the density of stars, and assuming hydrostatic equilibrium for the H I gas (see Eq. 2), with $\sigma_{\rm eff} = 9$ km s^{-1}. The stellar disk is assumed to be exponential with a local surface density of 35 M$_\odot$ pc^{-2} and a radial scalelength of 3.2 kpc.

Both curves show an increase of the HWHM as a function of distance, which is consequence of the decrease in the gravitational potential of the disk. However, it is apparent that the curves does not match at large radii. In particular, at the last measured H I point, the observed scaleheight is about 1.4 times the predicted value. Therefore, if we wish to keep our assumption that the halo is nearly spherical, one or more assumptions made to derive the flaring should not hold. Some possibilities include (1) breakdown of the assumption of hydrostatic equilibrium, (2) breakdown of the assumption that the disc is azimuthally symmetric because of the warp, the outer spiral arms, a triaxial halo, or any other agent, (3) accretion of a smooth flow, (4) the gas velocity dispersion is not constant with radius.

The sound crossing time over a scaleheight of ~ 1 kpc at the sound speed of 9 km s^{-1} is rather short. Thus, hydrostatic equilibrium is expected to be a valid approximation at any R (see also §IV for a discussion). Since the warp is an vertical $m = 1$ mode, it is unable to change significantly the azimuth average thickness of the disk. As already said in §II, the observed anticorrelation between surface density and thickness suggests that spiral arms do not produce a net departure from hydrostatic equilibrium in the outer disk, beyond the corotation radius. Therefore, Eq. (2) should be valid after azimuthal averaging. On the other hand, the modest triaxility of our halo ($0.9 \leq q \leq 1.1$) seems unlikely to produce a change in the flaring. Accretion of a smooth flow produces compression thereby reducing further the predicted thickness of the disk (e.g., Sánchez-Salcedo 2004). The only remaining possibility to explain the scaleheight with an isothermal spherical halo is by assuming that the velocity dispersion increases outwards. Interestingly, if turbulence is driven by accretion of clumpy gas, the radial dependence of σ depends on the radial dependence of the mass accretion rate per unit area $\dot{\Sigma}(R)$ and on the surface density $\Sigma(R)$, through the combination $\dot{\Sigma}/\Sigma$. An increasingly velocity dispersion with R is possible (Santillán et al. 2007). In the following, we estimate the accretion rate $\dot{\Sigma}(R)$ from an astrophysical-motivated model.

Benjamin & Danly (1997) consider a Galactic halo consisting of three components: the warm ionized layer of H II, the mean H I density distribution and the hot halo component with $T = 10^6$ K. While the two first were parameterized observationally, the third component was constructed theoretically by assuming an isothermal halo in hydrostatic equilibrium, with the midplane density matching the X-ray emission data of Garmire et al. (1992). Combining these three components, Benjamin & Danly (1997) suggest the volume density of hot gas n_h as a function of $z_{\rm kpc}$, the distance to the plane in *kpc*:

$$n_h(z) = 1.1 \times 10^{-3}\left(1 + \frac{z_{\rm kpc}^2}{19.6}\right)^{-1.35} \ {\rm cm}^{-3}. \qquad (4)$$

This implies that n_h decays one order of magnitude from $z = 15$ kpc ($n_h = 3.5 \times 10^{-5}$ cm^{-3}) to $z = 40$ kpc ($n_h = 3 \times 10^{-6}$ cm^{-3}). If we assume that the hot gas traces the distribution of HVCs and since the H I surface density decays a factor 340 in this range according to Eq. (1), the ratio $\dot{\Sigma}/\Sigma$ may increase a factor ~ 34. Santillán et al. (2007) discussed the effect of this huge radial variation of $\dot{\Sigma}/\Sigma$. Scaling their arguments, the velocity dispersion is expected to be between 9–13 km s^{-1}. Since the HWHM scales as $\propto \sigma_{\rm eff}^2$, we conclude that turbulence driven by accretion can account for the discrepancy between the observed and predicted thickness of the Galactic H I layer.

VI. SUMMARY

Extended disks of H I around spiral galaxies show a remarkably uniform velocity dispersion. Since stellar winds and supernovae are largely absent in such regions, neither the magnitude nor the constancy of the gas velocity dispersion can be accounted for in a scenario in which turbulence is driven by stellar energy sources.

In this paper we have explored other mechanisms to drive turbulence in the outer regions of galactic disks: spiral arms, ram pressure and cold gas accretion. We argue that it is unlikely that the observed outer spiral arms can maintain the homogeneous level of turbulence. Whilst the injection of energy to the ISM by the ram pressure of an hypothetical intergalactic medium might alter somehow the dynamics at the very outer rim of the H I disk, we find that the constant bombardment by tiny high-velocity halo clouds can be a significant source of random motions in the outer disk gas.

The accretion of clumpy gas may have very interesting implications for our understanding of the dynamical state of the outer extended H I gas in galaxies. In this paper we have discussed how the Galactic H I flare can be accounted for in a spherical dark halo. In addition, the large asymmetry in the scaleheight of the H I disk between the northern and southern halves of the disk may have a natural explanation in this scenario (Santillán et al. 2007). Moreover, accretion of cloudy gas can induce turbulence-compressed regions and trigger star formation. The probability of a region having Jeans mass gets higher with increasing Mach number, i.e. at high accretion rates. Star formation can still proceed in a self-regulated manner as bubbles, chimneys and the galactic wind eventually quench the gas infall.

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