High velocity gas from the Galactic dark halo

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Abstract. We present the germ of a new model for High Velocity Clouds, derived from the idea that the dark matter halo of our Galaxy is in the form of cold, planetary-mass gas clouds. In this picture HVCs arise as a result of disruptive collisions between dark matter clouds: high velocity atomic gas is a natural consequence of the dark halo kinematics, and is intimately associated with assembly of the visible Galaxy. Quasi-spherical halo models predict a broad 21 cm line background, together with a number of individually detectable, low-mass HVCs conforming to a particular velocity field. A halo model which incorporates satellite substructure – after the fashion of the current paradigm of hierarchical structure formation – includes both these components and, in addition, some massive HVCs. These latter HVCs are simply the wakes of the orbiting satellite halos, and each may have a mass up to 0.3% of the mass of the satellite.

1. Introduction

The suggestion that Galactic dark matter might be in the form of cold molecular gas clouds was made several years ago (Pfenniger, Combes & Martinet 1994). These authors proposed gas in the form of fractal agglomerates, distributed in a thin disk, but one might equally well imagine isolated clouds distributed in a quasi-spherical halo (Gerhard & Silk 1996). The attractiveness of this picture was greatly increased by the recognition (Walker & Wardle 1998a) that one infers such a halo from data on “Extreme Scattering Events” (Fiedler et al 1987). The cold clouds are deduced to be molecular, with individual masses \( \sim 10^{-3} \, M_{\odot} \); a summary of the relevant astrophysics will be given elsewhere (Walker & Wardle 1998b, PASA in preparation).

Another startling piece of evidence in favour of the cold cloud picture was uncovered by Walker (1998), who showed that this model offers a simple explanation for the dynamical regularities of spiral galaxies — specifically the disk-halo conspiracy and the Tully-Fisher relation. These regularities arise as a consequence of the conversion of dark matter into visible (warm, diffuse) gas, via the process of cloud-cloud collisions, and can be modelled with kinetic theory applied to isothermal halos. This discovery has served to focus our attention on collisions in connection with visible galaxy assembly. A basic feature of the collision process is that it populates the Galaxy with atomic gas moving in orbits which are quite distinct from the cold rotation of disk gas and so, as we shall
see, High Velocity Clouds are expected. In §2 we consider collisions occurring within an isothermal, spherical halo; §3 generalises this to a halo which has some rotational support; and §4 discusses a more realistic description in which the halo possesses sub-structure.

2. Spherical halo

The simplest Galactic halo model is the isothermal sphere. In the context of a cold cloud dark matter picture, this model gives some simple results against which one can usefully compare the data.

2.1. Atomic gas from molecular clouds

Sound speeds for the gas within the clouds are expected to be very low – 0.2 km s\(^{-1}\) in the model of Wardle & Walker (1998; ApJL in preparation) – in comparison with the relative speeds of clouds within the halo (several hundred km/s), so the most basic expectation is that strong shocks will be generated during collisions and these will unbind the gas. Providing only that the shock speeds exceed 24 km s\(^{-1}\) (Kwan 1977), the molecular gas in the clouds will be completely dissociated during a head-on collision. At higher speeds the ionised fraction increases (50\% H ionisation at \(\simeq 70\) km s\(^{-1}\); Shull & McKee 1979), being unity in the case of the Galactic halo (shock speeds \(\simeq 200\) km s\(^{-1}\)). In the dense (\(\sim 10^{12}\) cm\(^{-3}\)), post-shock gas, radiative cooling proceeds more rapidly than re-expansion, implying that most of the dissipated kinetic energy is radiated away – the ramifications of this are discussed elsewhere (Walker & Wardle, 1998c, in preparation). Thermal instability is present in the post-shock gas, resulting in hot, low-density gas in which cooler, denser blobs are embedded. Recombination of the ions is also very rapid, but molecular re-formation is relatively slow, and consequently, atomic gas is released into the Galactic halo in the case of head-on cloud-cloud collisions.

In the case of glancing collisions, a good part of the mass of the clouds escapes unshocked, and is not significantly decelerated. However, some fraction of the power radiated by the shocked gas will be absorbed by the unshocked material and, because the total radiated energy is many orders of magnitude larger than the clouds’ thermal energy, it is expected that complete unbinding will still occur. What is less certain is the material state of the unshocked gas, which could remain molecular. (Note, however, that shocks caused by subsequent interaction with the surrounding medium should even then convert the gas to atomic form.) In the following discussion we shall restrict attention to head-on collisions, and the subsequent fate of the gas released by such collisions.

2.2. Expansion and merging

The radiative phase of each collision reduces the temperature from \(T \simeq 5 \times 10^5\) K to \(T \simeq 6000\) K, at which point the radiation time-scale exceeds the expansion time-scale and subsequent evolution is approximately adiabatic. During this

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1Dwarf galaxies with internal velocity dispersions \(\lesssim 17\) km s\(^{-1}\) should consequently possess interstellar media which are predominantly molecular.
phase the gas expands at roughly $15 \text{ km}\cdot\text{s}^{-1}$ from $R \sim 10^{14} \text{ cm}$ to $R \sim 10^{18} \text{ cm}$; for most of this period the gas is so cold that it could be detected only in absorption. The expansion ceases to be adiabatic when the density has dropped to the point where interaction with the external medium becomes important. For an external density $\sim 10^{-2} \text{ cm}^{-3}$ (see §§2.4,2.5) this occurs roughly $10^4 \text{ yr}$ after the collision. At this point the material is re-heated to several thousand degrees by the passage of a shock, rendering it visible once more in emission. Subsequently – on a time-scale of order $10^5 \text{ yr}$ – the post-collision gas loses its kinematic identity as its velocity approaches that of the surrounding fluid.

2.3. Velocity field

As the constituents of a spherical halo have zero mean velocity field, predicting the native velocity field of post-collision gas is trivial: as seen from the LSR it is just $-V \sin \ell \cos b$, where $V = 220 \text{ km}\cdot\text{s}^{-1}$ is the circular speed of the LSR. Around this mean we expect a dispersion of $55 \text{ km}\cdot\text{s}^{-1}$, much smaller than for the pre-collision clouds ($155 \text{ km}\cdot\text{s}^{-1}$). This is a direct consequence of the fact that the collision process favours pairs of clouds having antiparallel velocities. Note that for as long as the gas remains kinematically distinct (separated in velocity by at least $100 \text{ km}\cdot\text{s}^{-1}$) from its surroundings, there is negligible acceleration in the Galactic potential, simply because this phase lasts for much less than an orbital period — $10^5 \text{ yr}$ versus $3 \times 10^8 \text{ yr}$.

2.4. Detectability of post-collision clouds

A key point to notice is that the low mass of the colliding clouds $\sim 10^{-3} \text{ M}_{\odot}$ renders the collision products individually undetectable unless they are very close to the Sun. Distances $\lesssim 70 \text{ pc}$ are required for the collision products ($\sim 2 \times 10^{-3} \text{ M}_{\odot}$) to be detectable by HIPASS (Staveley-Smith 1997), placing these clouds within the Local Hot Bubble. If the LHB density is $10^{-2} \text{ cm}^{-3}$ (Cox & Reynolds 1987), each expanding cloud will approach the LSR velocity on a time-scale $\sim 10^5 \text{ yr}$. This implies median angular radii of order $1 M_{-3}^{1/6} \deg$. From the cloud-cloud collision rate per unit volume (Walker 1998), we compute an expected HIPASS detection rate of order $1 M_{-3}^{5/6} \text{ sr}^{-1}$, where the mass of each cold cloud is written as $10^{-3} M_{-3} \text{ M}_{\odot}$.

The small number of individually detectable post-collision clouds indicates that this model is germane to only a fraction of the observed population. Moreover, some of the large HVC complexes now have distance constraints (van Woerden 1998) that exclude nearby, low-mass clouds. By the same token, though, at least one HVC of sub-solar mass is known (van Woerden 1998), so the model may indeed be relevant to a subset of the observed HVC population.

2.5. 21 cm background

As noted above, the expanding gas from individual collisions is not detectable unless the collision occurred very local to the Sun (roughly, within the Local Hot Bubble). As the halo extends well beyond this volume, we see that the bulk of the post-collision population should manifest itself as an unresolved background. This population is born kinematically cold (velocity dispersion $55 \text{ km}\cdot\text{s}^{-1}$), and therefore inadequately supported in the Galactic potential. Infall will occur,
presumably at a speed comparable to the typical sound speed in the flow. We estimate that this is \( \sim 10 \, \text{km s}^{-1} \) – neutral gas at several thousand Kelvin – implying an infall time of order \( 4 \times 10^8 \) yr. Shock heating will create localised regions which are hotter, and may be highly ionised, but cooling and recombination are, at a density \( \sim 10^{-2} \, \text{cm}^{-3} \), relatively rapid. Given the cloud-cloud collision rate per unit volume (Walker 1998) it is straightforward to deduce the rate per unit area towards the Galactic poles, say. Knowing the infall time-scale then allows us to deduce a high-latitude column of \( N_H \sim 10^{20} \, \text{cm}^{-2} \) in warm, predominantly neutral gas.

We are unable to give quantitative predictions for the velocity field of this fluid as a whole; qualitatively we can say that the gas should be sub-rotating (relative to the disk) and infalling. Turbulence is expected to be present as a consequence of the ongoing injection (with velocity dispersion \( 55 \, \text{km s}^{-1} \)) of fresh gas, from recent collisions. Shocks will tend to damp any turbulence; on the other hand, kinetic energy liberated by infall will tend to sustain it.

Despite the uncertainties, the characteristics we anticipate for the infalling halo gas are somewhat reminiscent of the large velocity dispersion component \( (\sigma_v \approx 60 \, \text{km s}^{-1}, \, N_H = 1.4 \times 10^{19} \, \text{cm}^{-2}) \) discovered in the 21-cm Leiden-Dwingeloo Survey (Kalberla et al 1998). We caution that such a large velocity dispersion component has not been identified in previous HI surveys (Dickey & Lockman 1990).

3. Rotating halo

Given that the visible disk of our Galaxy is almost entirely supported by its rotation, and in our model this material was originally part of the dark halo, it is important to consider halo rotation. Analytic models of rotating isothermal halos have been given by Toomre (1982). However, unless a large amount of rotation is invoked – a possibility which would be difficult to understand in the context of a tidal torquing origin for halo angular momentum – the discussion in the previous section is only changed slightly. The most significant change is that the apparent native velocity field of post-collision clouds becomes \( \langle v_\phi \rangle - V \sin l \cos b \), with a dispersion of roughly \( 55 \, \text{km s}^{-1} \). In principle, comparison with an observed velocity field could admit a measure of the halo rotation speed, \( \langle v_\phi \rangle \), but interaction with low velocity disk gas renders this a difficult procedure.

4. Structured halos

Even if one does not entirely subscribe to the current paradigm of hierarchical formation of structure in the Universe (see, e.g., Peebles 1993), one still expects galaxy halos, including the Galactic halo, to incorporate substructure, as a consequence of the accretion of smaller satellite galaxies. This modifies the picture of \( \S \S 2,3 \) substantially by introducing both density and velocity structure, and we can no-longer give unique predictions because the nature of these structures is not known \textit{a priori}. Nevertheless we can outline some general features as follows.
Figure 1. A satellite composed of cold clouds (filled circles) moving through a background of similar clouds (open circles) comprising the quasi-spherical component of the Galactic dark halo. Collisions occurring between these two sets of clouds lead to a wake of diffuse atomic gas behind the satellite.

For any given satellite we can imagine the dark matter as following a single orbit, with a relatively small space/velocity dispersion, at an orbital speed of order the Galaxy’s circular speed ($V$) — as per figure 1. Associated with this satellite there are two types of cloud-cloud collisions to contemplate: those where clouds within the satellite collide with each other, and those where one of the colliding pair is part of a kinematically separate component of the Galaxy’s halo. In particular we shall assume this second component to be a quasi-spherical background of dark matter, as per the model halo considered in §2. For collisions occurring between clouds within the satellite, the post-collision gas remains bound to the satellite (though it may subsequently be stripped out by ram pressure). If this process dominates it presumably leads to a recognisable satellite galaxy, with its own stars and interstellar medium.

For a satellite interior to the dark halo core radius of the Galaxy – i.e. about 6 kpc (Walker 1998) – the dominant process is expected to involve “satellite clouds” colliding with “spherical halo clouds.” The centre-of-mass velocity for this type of collision differs by $\sim V/2 \sim 100 \text{ km s}^{-1}$ from the satellite’s orbit, and is thus very unlikely to be bound to it. (Notice, also, the trivial point that a tidally disrupted satellite halo – i.e. a stream of dark matter – cannot bind
gas released in any type of collision.) In consequence we expect satellite halos to leave behind them a trail of gas.

The details of the collision process itself, and subsequent adiabatic phase, do not differ sufficiently from the case of the spherical halo (§§2.1,2.2) that they warrant separate discussion. The merging process, on the other hand, is slightly different. A qualitative distinction is that there is no ongoing injection of gas (hence kinetic energy) into the wake downstream from the satellite: there is only “fossil turbulence”, which is damped by conversion into thermal energy. Quantitatively we note that the velocity dispersion of the merging gas is larger — up to 80 km s$^{-1}$. This is because the satellite halo has a velocity dispersion that is small in comparison to that of the Galactic halo, so the velocities of the colliding cold clouds do not cancel as effectively as in the case of collisions within a simple spherical halo. As a result the temperatures reached by gas in the wake may initially be as high as $10^5$ K, but radiative cooling rapidly brings this down to values less than $10^4$ K, and the gas will recombine on a time-scale $\sim 10^7$ yr.

A purely dark satellite of mass $M_{sat}$ moving on an approximately circular orbit around the Galaxy will leave behind gas at the rate $-\dot{M}_{sat} \simeq 8\rho V M_{sat}/\Sigma$, where $\rho$ is the density of the spherical component of the Galaxy’s dark halo, and $\Sigma \simeq 130$ g cm$^{-2}$ (Walker 1998) is the mean surface density of the individual dark clouds. (Note that the collision cross-section for pairs of identical clouds is four times the geometric cross-section of a single cloud, because even glancing collisions will unbind the gas.) For a satellite orbiting near the solar circle, we then expect that between successive crossings of the Galactic plane a mass of roughly $3 \times 10^{-3} M_{sat}$ will be deposited in the wake.

Evidently it is possible to explain the masses, at least, of the large complexes of HVCs (van Woerden 1998) if one contemplates satellite dark halos as massive as $10^9 M_\odot$. Because satellite orbits can be retrograde, with respect to the Galactic disk, these wakes may display LSR velocities of magnitude $\sim 2V \sim 400$ km s$^{-1}$, and may thus be relevant to the Very-HVCs (Wakker & van Woerden 1997). Of course, the trajectory of the gas wake differs substantially from that of the satellite itself. Crudely speaking, gas is injected into the wake with a mean velocity parallel to, but only half as large as the satellite’s velocity; acceleration in the Galactic potential subsequently pulls the wake progressively further away from the satellite’s trajectory as it progresses downstream. Consequently these wakes are expected to display a substantial degree of infall in their kinematics.

5. Summary

The combined model of a quasi-spherical Galactic halo (§§2,3) with satellite substructure (§4), and cold clouds making up the dark matter, gives a rich theoretical picture of high velocity atomic gas arising from cloud-cloud collisions. The quasi-spherical component leads one to expect a small number of low mass HVCs located in the Local Hot Bubble, and conforming to a simple velocity field. These HVCs are just the nearest examples of a much larger population, which gives rise to a background of broad 21 cm emission. Generalising to a model which includes satellite substructure within the dark halo leads us to expect gaseous wakes containing large quantities of high velocity atomic gas. These wakes may be relevant to the observed complexes and streams of HVCs,
including the Magellanic Stream. We emphasise, however, that a satellite galaxy – i.e. including stars – is not required as the wake is produced by dark matter.

This paper presents some ideas on how the cold-cloud picture of dark matter may help us to understand the presence of high velocity gas in our Galaxy; but it is interesting to ask “What do HVCs tell us about dark matter?” (In the context of our model, of course!) Obviously one could learn a great deal about the structure of the dark halo of our Galaxy, and in turn this would inform us about halo formation and so on. However, the most significant point at present seems to be the fact that HVCs contain metals, while the model dictates that they should be composed of primordial gas. One could take the view that this rules out the model, if one had complete faith in the conventional perspective on Big Bang nucleosynthesis. Alternatively one could argue that the gas has been “polluted” by a population of massive stars in the early Universe; or perhaps that the metals actually come from diffuse Galactic gas swept up by the expanding post-collision material? Nevertheless we caution that the metallicity of primordial gas must, ultimately, be determined by observation.

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