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High-velocity clouds as dark matter in the Local Group

M. López-Corredoira, J.E. Beckman, and E. Casuso

Instituto de Astrofísica de Canarias, 38200 La Laguna, Tenerife, Spain

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Abstract. The High-Velocity Clouds (HVCs) observed in the Galactic neighbourhood, have been proposed to be remnants of the formation of the galaxies in the Local Group, having distances, and thus masses, predominantly of dark matter, considerably larger than hitherto hypothesized. This hypothesis is plausibly supported by observational evidence that their kinematical centre is the Local Group barycentre. Evolutionary models to account for the evolution of the light elements in the Galaxy demand infall of metal poor gas to the plane, which could well be supplied by these HVCs. Modelling the time dependence of this infall, taking into account that an accreting galaxy shows an increasing cross-section to the infalling clouds, and produces increasing mean infall velocities, we deduce that the HVCs must currently represent at least around one half of the total mass of the Local Group, given that the accretion rate, as inferred from chemical evolution, has not decreased significantly during the disc lifetime. This fraction is consistent with dynamical estimates of the relative masses of the Local Group as a whole and its constituent galaxies. The HVCs may thus form a significant constituent of baryonic, and of non-baryonic, dark matter.

Key words: galaxies: intergalactic medium – ISM: clouds – galaxies: Local Group – cosmology: dark matter

1. Introduction

High-velocity clouds (HVCs) consist of neutral hydrogen at radial velocities approximately $|v_{\rm LSR}| > 90\,{\rm km\,s^{-1}}$, incompatible with a simple model of differential galactic rotation (Wakker & van Woerden 1997). Their range of radial LSR velocities extends indeed up to -500 $\rm km\,s^{-1} < v_{\rm LSR} <$+300 $\rm km\,s^{-1}$. Several hypotheses try to explain the origins of the HVCs (see review in Wakker & van Woerden 1997; Wakker et al. 1999b). At least three different sources appear to be needed: one for the Magellanic Stream and related clouds, one for the Outer Arm Extension, and at least one for the "other HVCs" (Wakker & van Woerden 1997).

One hypothesis, recently put forward by Blitz et al. (1999, hereafter BL99) as the most plausible one to explain "other" HVCs, claims that they are remnants of the formation of the Local Group at a scale distance of 1 Mpc, i.e. far from the Galaxy. These clouds are falling towards the Local Group barycenter and some of them will be accreted by the Milky Way if they move close enough to it.

Here, we hypothesize that these clouds may constitute a major fraction of the mass of the Local Group. The fraction of sky covered by HVCs with $|v_{\rm LSR}| > 100\,{\rm km\,s^{-1}}$ and $N({\rm HI}) > 2\times10^{18}\,{\rm cm^{-2}}$ is 8%, excluding the Outer Arm Extension and the Magellanic Stream (Wakker 1991). If they are relatively distant, as the estimated mass of a cloud is proportional to d^2 (d is the distance), they could represent a larger contribution to the mass of the Local Group than hitherto assumed.

2. Accretion theory

The view of HVCs as gas being accreted by the Galaxy was first suggested by Oort (1966, 1970), who postulated that gas left over from the formation of the Galaxy is now reaching the Galactic disc. During their approach, the clouds are heated and recooled forming the HVCs at heights of 1 to 3 kpc. A simple model with the Galaxy accreting these clouds encounters directly many problems; for instance, it cannot justify observations with positive velocities. The possibility of an extragalactic origin of these clouds associated with the Local Group was discussed by Verschuur (1969, 1975), Einasto et al. (1976), Eichler (1976), Giovanelli (1980, 1981), Arp (1985), Bajaja et al. (1987) and others, but their models apparently failed to fully explain the observations.

The difficulties of this hypothesis were solved in BL99 aided by new observational evidence. The kinematic anomalies are explained in terms of the infall of remnants of the formation of the Local Group towards its barycentre. A typical cloud at a distance of 1 Mpc has a diameter of 30 kpc and contains 3.5×10^7 $\rm M_\odot$ of HI gas, and a total mass of $\sim 3\times10^8$ $\rm M_\odot$ (given 85% of dark mass). Its density would be $\langle n_{\rm HI}\rangle \approx 10^{-4}\,{\rm cm^{-3}}$. Braun & Burton (1999) analyzed a sample of HVCs similar to that of BL99, but chose isolated clouds, avoiding the contamination of some complexes related to the Magellanic Stream or the Outer Arm Extension, finding a size of 15 kpc and a similar HI mass. The dynamics of the Local Group is dominated by the attraction of M31 (with twice the mass of the Milky Way) and the Milky

Send offprint requests to: martinlc@iac.es

Way. When a cloud is within 100 kpc comoving distance of one of these galaxies it can be taken as accreted. The simulated spatial and kinematic distributions resemble the observed distributions rather well. Most of the HVCs are located either near the direction of M31, towards the barycenter of the Local Group, or in the antibarycenter direction. The distribution of velocities with angular distance from the solar apex is that expected for Local Group barycentre infall (Braun & Burton 1999).

Low metallicity is observed in some HVCs. Sembach et al. (1999) observed some highly ionized HVCs whose ionic ratios are well explained via photoionization by extragalactic background radiation combined with some ultraviolet starlight. The observations by Tufte et al. (1998) of a set of HVCs also suggest photoionization. Hence, these clouds must have low density ($n_{\rm H} \sim 10^{-4}\,{\rm cm}^{-3}$), and be bigger than a few kpc and mainly ionized ($n_{\rm HI}/n_{\rm H} \sim 10^{-3}$), which indicate that they must be far away from the neutral Galactic gas. These clouds would have total masses of $\sim 10^8$ $M_\odot$. If the clouds are intergalactic in nature, their metallicities could well be $[Z/H] \sim -1$ or lower. Low metallicities were also detected in an HVC through sulphur abundance measurements, yielding $[S/H] = 0.094$ times solar, much lower than the solar value (Wakker et al. 1999a). This metallicity supports the extragalactic origin at least for this object because gas ejected from the current Galaxy would share its near-solar metallicity.

As an additional datum, it is observed that the HVCs properties are similar to those found for high redshift "Lyα forest" clouds (BL99). This implies that this type of clouds is also abundant at very large distances from the Local Group and that they are present in the primordial scenarios of galaxy formation.

3. Chemical evolution of the Galaxy

If HVCs are extragalactic, the chemical evolution of the Galactic disc is strongly affected by continual but episodic infall of metal-poor gas from HVCs which mixes slowly with the rest of the interstellar medium.

The infall rate of low metallicity gas should be increasing now, or at least remain constant on timescales compared to the Hubble time. The reasons which sustain this hypothesis are based on a interpretation of the chemical evolution in the local Galactic disc:

- The G-dwarf distribution in the solar neighbourhood (Rocha-Pinto & Maciel 1996) with a sharp rise in numbers close to $[Fe/H] = -0.2$ requires either a sharp increase in the SFR (stellar formation rate) at that metallicity, or the accumulation of stars formed at different epochs but at the same metallicity and both can be explained using a rising or near constant infall rate of metal-poor gas.
- Star formation in the past 5 Gyr has a long-term average slow-rise according to stellar activity data (Vaughan & Preston 1980, Barry 1988).
- The ^{9}Be abundance plotted versus iron abundance has a loop-back close to $[Fe/H] = -0.2$, implying a fall in Fe abundance while ^{9}Be abundance increases, which can be well explained with a rising infall rate (Casuso & Beckman 1997).

An inference presented in BL99 is that the accretion of gas in the Milky Way is decreasing. The present value would be 7.5 $M_\odot$/yr. However, in their simple dynamical model, they do not take into account the increasing gravitational potential of the discs due to the accretion itself. The increasing mass of our Galaxy could counterbalance the declining density of the baryonic material in the intergalactic medium leading to an increasing accretion rate of material into the Galaxy. This will be discussed quantitatively in the next section.

4. Total mass of the clouds in the Local Group

The accretion rate depends on the spatial density of the clouds ($\langle\rho_{\rm clouds}\rangle$), their mean velocities ($\langle v\rangle$) and the cross section of galaxies to trap a cloud ($\Sigma_{\rm g}$). These three factors govern the dynamics:

$$\frac{dM_{\rm g}}{dt} \propto \langle\rho_{\rm clouds}\rangle\langle v\rangle\Sigma_{\rm g}, \tag{1}$$

where $M_{\rm g}$ is the mass of the accreting galaxies plus their neighbour satellites; the main components are the Milky Way and M31.

BL99 take the second and third factors as constants but this is too simplistic. The three factors are respectively:

Density. The density can be expressed simply via:

$$\langle\rho_{\rm clouds}\rangle = \frac{M - M_{\rm g}}{V}, \tag{2}$$

where M is the total mass of the Local group (constant, assuming that the local group does not exchange mass with any external reservoir) which includes the mass of the clouds and the galaxies ($M_{\rm g}$). Any ionized intercloud medium would make an extra contribution to the mass of the Local Group; although we do not include it explicitly here, its gravitational behaviour would be akin to that of the clouds. V is the physical volume of the Local Group, which is constant (we can assume that the Hubble expansion is neutralized on the scale of the Local Group since the cluster is gravitationally bound and collapse, if any, is very slow).

Velocity. The velocity depends on the masses of the accreting galaxies. When the cloud approaches a centre of accretion, the average velocity of the cloud with mass $m_{\rm c}$ is:

$$\frac{1}{2}m_{\rm c}v_1(r_1)^2 = s\frac{GM_1 m_{\rm c}}{r_1}, \tag{3}$$

where r_1 is the distance to the accreting galaxy of mass M_1 and $v_1 = \left|\frac{d\boldsymbol{r_1}}{dt}\right|$, the velocity with respect to this object. $\langle s\rangle$ depends on the mean energy of the clouds; $s = 1$ if they have escape velocity, $s = \frac{1}{2}$ for a virialized system; etc. Masses of other objects have a negligible effect when the cloud is quite close to a galaxy, so, roughly, the velocity is proportional to $M_1^{1/2}$. In our case, there are two accreting centres and the relation is more complicated. Eq. (3) applies near the mass M_1. Near the mass M_2, the average velocity of the clouds is:

$$\frac{1}{2}m_{\rm c}v_2(r_2)^2 = s\frac{GM_2m_{\rm c}}{r_2}, \quad (4)$$

where r_2 is the distance to the accreting galaxy of mass M_2 and $v_2 = \left|\frac{dr_2}{dt}\right|$. Therefore, the velocity is proportional to $M_2^{1/2}$.

In the region dominated by the barycentre rather than each individual galaxy, we can take $M_{\rm g} + C(M - M_{\rm g})$ as the equivalent mass of the centre of attraction. The first term is due to the galaxies ($M_{\rm g} = M_1 + M_2$) and the second is the mass of the clouds which are inside the spherical region centred on the barycentre, and radius the distance to it. Since the distance is a variable, C (the fraction of the mass in clouds in that region: between 0 and 1) is variable, but we can take an average value for C to tipify infall of the clouds. The continuous increment of kinetic energy during infall is the sum of terms due to the galaxies and the clouds; hence, the total increment is the sum of two terms: one proportional to $M_{\rm g}$ and another one proportional to $(M - M_{\rm g})$.

Near the galaxies, making the reasonable assumption that $M_1/M_{\rm g}$ and $M_2/M_{\rm g}$ are constants, i.e. the ratio of the masses of the two galaxies does not change and the velocity of the galaxies with respect the barycentre is negligible compared with that of the clouds, the mean infall velocity ($v_1 = v_2 = v_{\rm bar}$) will be proportional to $M_{\rm g}^{1/2}$, i.e. $C = 0$. The mean velocity is, in general, proportional to $\sim (M_{\rm g} + C(M - M_{\rm g}))^{1/2}$ where C is an averaged quantity along the path of the clouds and lies between 0 and 1 (v^2 is proportional to $(C_1 M_{\rm g} + C_2(M - M_{\rm g}))$, since in the proximity of the galaxy i, $C_1 = M_{\rm i}/M_{\rm g}$, while on the rest of the path $C_1 = 1$, but this is solved by dividing the expression for v^2 by the average C_1; so $C = C_2/C_1$).

The velocity may be slightly reduced by interaction with the disc, via collision of the high-velocity gas with the stationary disc gas (see calculations in Tenorio-Tagle et al. 1987, 1988; Comeron & Torra 1992, 1994). If drag forces dominate, the velocity becomes proportional to the square root of the column density. Benjamin & Danly (1997) found that intermediate-velocity clouds with low column densities may well reach terminal velocity, but HVCs should be hardly slowed down. As their time of interaction with the disc is relatively short, the effects of drag are negligible and the velocity can be calculated without taking them into account.

Collision cross section of galaxies for the clouds. This is proportional to the square of the disc radius of the galaxy. In an essentially two-dimensional disc, such as that of a spiral galaxy, we can assume a dependence of the radius on the mass of form $L \propto M^{1/2}$. This is in fact found observationally. In the plot of the radii vs. the masses of a sample of $S_{\rm b}$ galaxies (Campos-Aguilar et al. 1993), a relation $L \propto M^{0.49\pm0.06}$ is fitted. Since M31 is an $S_{\rm b}$ galaxy and the Milky Way is an $S_{\rm bc}$, we can use this relationship for these objects and take the cross section to be proportional to L^2, i.e. proportional to $M_{\rm g}$.

Therefore, the accretion rate follows:

$$\frac{dM_{\rm g}}{dt} = \frac{K}{V}(M - M_{\rm g})[M_{\rm g} + C(M - M_{\rm g})]^{1/2}M_{\rm g}, \quad (5)$$

where K is a positive constant.

The factor $(M - M_{\rm g}) > 0$ falls with time thereby reducing the accretion rate for the Milky Way, but $(M_{\rm g} + C(M - M_{\rm g}))^{1/2}M_{\rm g}$ increases yielding an increase with time. Whether the net rate increases will depend on the ratio of the masses of the major galaxies to the integrated mass available for accretion in the clouds.

If the accretion rate is increasing or at least constant, as argued in the previous section, the minimum limit implied for the fractional mass of the HVCs in the Local Group can be evaluated and compared with observational parameters. The condition for the rate to be increasing with the time at the present epoch is that its derivative be greater than zero:

$$\frac{d^2M_{\rm g}}{dt^2} = \frac{K}{V}(-[M_{\rm g} + C(M - M_{\rm g})]^{1/2}M_{\rm g}$$

$$+(M - M_{\rm g})M_{\rm g}(1 - C)[M_{\rm g} + C(M - M_{\rm g})]^{-1/2}/2$$

$$+(M - M_{\rm g})[M_{\rm g} + C(M - M_{\rm g})]^{1/2})\frac{dM_{\rm g}}{dt} > 0$$

$$\Rightarrow M_{\rm g} < \frac{4C}{\sqrt{9C^2 - 2C + 9} - 3 + 7C}M, \quad (6)$$

$$M_{\rm clouds} = M - M_{\rm g} > \frac{\sqrt{9C^2 - 2C + 9} - 3 + 3C}{\sqrt{9C^2 - 2C + 9} - 3 + 7C}M. \quad (7)$$

This gives us a minimum fraction of mass for the clouds within the Local Group which is between 40% and 50%, depending on the value of C (between 0 and 1). Although this result is approximate, it is qualitatively plausible: a low fraction of mass in clouds would not yield increasing accretion as the mean cloud density would fall more quickly than could be compensated by the increasing gravitational attraction of the accreting galaxies.

This result is in very fair agreement with the dynamical estimates of the total mass of the local group, $\sim 3 \times 10^{12}$ $M_\odot$ (Byrd et al. 1994), in which well over the half of mass is not in the baryonic masses of detectable galaxies. The HVCs would constitute much of the non-galactic mass of the Local Group, they would be at least a significant part of the dark matter in the Local Group. One can speculate that the dark matter (the difference between the total mass of the cluster and the sum of the masses of the individual galaxies) in all clusters of galaxies is due in significant degree to such clouds.

We can infer that the minimum mass of the clouds in the Local Group is ~ 1.2–1.5×10^{12} $M_\odot$, i.e. around 5000 clouds with an average mass of $\sim 3 \times 10^8$ $M_\odot$. Since the Milky Way mass, from its rotation curve within the inner 15 kpc, is around 2×10^{11} $M_\odot$ (Honma & Sufue 1996), M31 has around twice this mass, and the rest of the galaxies also contribute a little, we can postulate that $\sim 2 \times 10^{12}$ $M_\odot$ is the maximum mass of the clouds given the above value of the total mass for the Local Group.

The clouds are not homogeneouly distributed, and most of them should be at a distance of $d \sim 1$ Mpc. The mean column density expected from them would be:

$$\langle N(\mathrm{HI})\rangle_{\mathrm{sky}} = \frac{M_{\mathrm{clouds}} f\, N_{\mathrm{A}}}{4\pi d^2}, \tag{8}$$

where f is the fraction of gaseous hydrogen ($f = 0.15$ according to BL99) and N_{A} is Avogadro's number. The result is $\langle N(\mathrm{HI})\rangle_{\mathrm{sky}} \sim 2 \times 10^{18}\,\mathrm{cm}^{-2}$, whose order of magnitude is in agreement with observations (Wakker 1991). The column density extends over the range $2 \times 10^{17}\,\mathrm{cm}^{-2} < N(\mathrm{HI}) < 2 \times 10^{20}\,\mathrm{cm}^{-2}$, and the observed average would be somewhat lower than $2 \times 10^{18}\,\mathrm{cm}^{-2}$ for $|v_{\mathrm{LSR}}| > 100\,\mathrm{km\,s}^{-1}$; although this difference might be due to the non-inclusion of intermediate velocity clouds as well to scatter in the parameters used (M_{clouds}, f, d).

5. Dark matter in HVCs and galaxies

Most of the HVC mass is dark matter, around 85% of the mass of the clouds. The nature of this dark matter is unknown. The dark matter in the HVCs could be some kind of baryonic matter; at least, this is compatible with the nucleosynthesis values: the baryonic matter is limited to 0.018$< \Omega_{\mathrm{b}} h^2 <$0.022 (Schramm & Turner 1998) while the observed local stellar density is a 17% of that (Fukugita et al. 1998).

This does not mean that all dark matter has to be baryonic, but the total mass of these clouds could be in baryons. Baryonic dark matter exists (Silk 1996) and a fraction of half of the mass of the Local Group is not excluded by primordial nucleosynthesis of the light elements. Very low mass stars, cold hydrogen and other exotic matter are some candidates. Models derived in part from the observations predict a scenario in which molecular clouds and dark clusters of MACHOs constitute the halo (De Paolis et al. 1995), or very cold molecular hydrogen in the disc (Pfenninger et al. 1994). These may also constitute scenarios for the dark matter in the HVCs.

Since a significant fraction of the present disc material proceeds from HVC accretion, part of the dark matter in the Galactic halo and disc is the same kind of material as the dark matter of the HVCs although the fraction may be different. From Eq. (5), the accretion rate can be derived for any time. For instance, assuming a present rate in the Milky Way of 7.5 $M_\odot$/yr (BL99), twice this for M31 and the total mass of the Local Group $\sim 3 \times 10^{12}$ $M_\odot$, we find that less than 30% of M_{g} has come from the accretion of HVCs during the last 15 Gyr. This is much less than the predictions by BL99, who conclude that practicaly all the mass of the two major disc galaxies should be due to the accretion of HVCs, mainly during early epochs. Unless its non-baryonic nature implies a process which favours only the retention of the baryonic components, this would imply that less than 25% of the matter of the Milky Way or M31 may be constituted by the kind of dark matter which is present in the HVCs. To this fraction, one should, of course, add the dark matter which entered into the constitution of the galaxies when they formed.

6. Conclusions

Using essentially the BL99 model for HVCs and a non-decreasing accretion rate of these clouds with low metallicity onto the Milky Way, we have deduced that their present abundance in the Local Group must be greater than some 40% to 50% of its total mass. This is in agreement with the dynamical measurements of the total mass in the Local Group and may account for a significant fraction of the baryonic dark matter, although a major fraction of non-baryonic matter within these clouds is not excluded. The calculations shown here are a first approximation, in which collapse or expansion of the Local Group was not taken into account but, the volume variation, if any, should be slow enough for us to neglect its effects.

At present, the nature of this dark matter (around 85% of the total mass of the clouds) cannot be determined, but the hypothesis of an important contribution to the total mass of the Local Group may be a clue towards finding it. Rotation curve anomalies and warps (Jiang & Binney 1999) in spiral galaxies could also be due to the existence of these HVCs, as a response to the torque the HVC system can exert on the disc of a large spiral.

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