Accretion by Galaxies

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**Abstract.** Both theory and observation indicate that galaxies like the Milky Way accrete matter at the rate of a few $M_\odot$ per year.

1. Introduction

The Milky Way is an extremely typical galaxy in the sense that most of the luminosity in the Universe comes from similar systems. Therefore, indications that the Milky Way is accreting at a significant rate would imply that accretion is an important phenomenon within the Universe at large.

Several observations suggest that material is falling into the Milky Way. First and foremost, our nearest large neighbour, M31, is approaching us at $\sim 140 \text{ km s}^{-1}$. Second, the so-called ‘high-velocity clouds’ have, on the average, negative line-of-sight velocities. Third, the Magellanic Clouds are on an orbit that must be decaying through dynamical friction, and I shall argue that the orbit of the Sagittarius Dwarf Galaxy is in a still more advanced state of decay. Fourth, beyond $\sim R_0$ the Galactic disk has a complex warped structure, and the most plausible explanation of this phenomenon invokes infall as the driver. Fifth, at a given radius the ISM appears to vary significantly in metallicity from place to place, and this phenomenon is most naturally explained by persistent accretion of low-metallicity material.

In this talk I shall review each of these lines of evidence in turn.

2. Collapse of the Local Group

The luminosity of the Local Group is dominated by the Milky Way and M31. Since M31 is approaching us, the Local Group is either virialized or collapsing. The simplest dynamical model in which the Group’s mass is concentrated in point particles coincident with the Milky Way and M31 suffices to show that the age of the Universe, combined with the present distance and Galactocentric velocity of M31, implies that the Local Group is collapsing for the first time (Kahn & Woltjer 1959).

When a cosmological structure collapses for the first time, its constituent parts move on highly elongated orbits towards the barycentre. Some of these orbits must enter the Galactic halo and become trapped. How much matter is the Galaxy likely to be accreting in this way?

The answer depends on two related quantities: how far out the Galactic halo reaches, and what fraction of the Local group lies outside M31 and the Galaxy.
The mass of the Local Group has been estimated many times and found to lie in the range $4 \times 10^{12} M_\odot$ (e.g., Schmoldt & Saha 1998). If all this matter were in M31 and the Galaxy, with a third of the matter being in the Galaxy, the halo would have to extend at constant $v_c = 220 \text{ km s}^{-1}$ to 120 to 210 kpc. Consequently, material that comes within $\sim 100 \text{kpc}$ of the Galactic centre is likely to be accreted.

Blitz et al. (1999) describe a simulation of the formation of the Local Group in which $10^6$ test particles move in the field of two point masses representing M31 and the Galaxy, plus the tidal field generated by external galaxies from Raychaudhury & Lynden-Bell (1989). Particles that come within 100 comoving kpc of either M31 or the Galaxy are captured. In the simulation the Hubble flow currently reverses $\sim 1.5 \text{Mpc}$ from the centre of the Local Group and the Galaxy’s current accretion rate is $\sim 7.5 M_\odot \text{yr}^{-1}$, of which $\sim 0.8 M_\odot \text{yr}^{-1}$ takes the form of neutral hydrogen.

Can we see infalling material? One school of thought has long held that the so-called high-velocity clouds (HVCs) are made of infalling gas (Oort 1966, 1970). HVCs were first identified when Muller, Oort & Raimond (1963) detected 21-cm emission in many directions at velocities that are incompatible with circular rotation. The location of the objects responsible for this emission has been controversial, however. One possibility is that they are small, nearby clouds that have been accelerated to large peculiar velocities by supernovae, stellar winds, and the like. Alternatively, they might be at distances in excess of a Mpc and be tracing the (disturbed) Hubble flow around the Local Group.

It is likely that no single explanation applies to all HVCs. Some of these objects are almost certainly associated with Local-Group galaxies such as M31, the Magellanic Clouds and the Phoenix dwarf spheroidal (St-Germain et al., 1999). Others, such as Complex A (van Woerden et al., 1998) and Complex M (Dailey et al., 1993) are small clouds in the Galactic halo. But a powerful case can be mounted that many HVCs are systems over 10 kpc in diameter that lie at distances $\sim 1 \text{Mpc}$.

Braun & Burton (1999) identified a sample of 66 compact, isolated HVCs, 23 of which had not previously been catalogued. They showed that these objects are distributed fairly uniformly over the sky, define a mean velocity that, within the errors, agrees with the Local Group’s mean velocity (Karachentsev & Makarov, 1966), and with respect to this mean have a velocity dispersion of 69 km s$^{-1}$ and an infall velocity $\sim 100 \text{km s}^{-1}$. They infer that these objects are typically $\sim 15 \text{kpc}$ in diameter and contain $\geq 10^7 M_\odot$ of HI.

Blitz et al. (1999) point out first that HVCs are seen within the Galactic plane where local objects would collide at high velocity with gas in circular motion, yet there is no evidence for shock-excited gas. Second, attempts to detect HVCs in absorption against distant stars have been largely fruitless – only two HVCs have been detected in absorption, and there are other reasons for believing that these are two of three HVCs that are unusually nearby. Third,

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$^1$The Local Group’s V-band luminosity is $\sim 4.2 \times 10^{10} L_\odot$ (e.g., Tables 2.1 and 4.3 of Binney & Merrifield, 1998), while the mean mass-to-light ratio of the Universe is $400h(\Omega/0.25)$ ($^\|$10.3.1 of Binney & Tremaine, 1987), so for $h = 0.65$ one expects the mass of the Local Group to be $1.1 \times 10^{13}$. 

nearby clouds would be illuminated by UV photons from the Galaxy and be brighter Hα sources than they actually are. Fourth, the velocities of the HVCs make more sense when referred to the barycentre of the Local Group than when referred to either the velocity of the Galactic centre or the Local Standard of Rest. Fifth, the metallicities of HVCs are low, which is inconsistent with their having been ejected from the Galactic ISM.

Blitz et al. use their simulation of the formation of the Local Group to show that the non-uniform distribution of HVCs on the sky arises naturally if HVCs lie at distances $\gtrsim 1 \text{Mpc}$. Moreover, at such distances the HVCs would have a distribution over column density which resembles that of Lyα clouds, which are now known to be floating in intergalactic space (Theuns & Efstathiou, 1998; Davé et al. 1999). Hence, when the HVCs are interpreted as extragalactic objects, they fit naturally into the picture of intergalactic space that has emerged from a combination of theoretical and observational work in cosmology. Blitz et al. argue that objects lying near the top of the HVC mass spectrum have already been detected in external groups of galaxies, and that less massive objects are detectable with feasible deep observations. They estimate that a typical cloud contains $3 \times 10^7 \text{M}_\odot$ of HI, so the population as a whole contains $\sim 10^{10} \text{M}_\odot$ of HI.

Once one accepts that many HVCs are extragalactic and associated with cosmic infall, it is inevitable that their detected hydrogen is associated with a very much larger mass of dark matter. The estimate of the Galaxy’s accretion rate cited above is based on the assumption that there is 10 times as much dark matter as neutral hydrogen. There could easily be more dark matter by a factor of a few, since $\Omega_{\text{baryon}}$ is thought to be $\lesssim 0.05$ and only a fraction of a HVC’s hydrogen content will be neutral.

3. Warps

Both theoretical and observational developments over the last few years have strengthened the argument that warps such as that of the Galactic disk are a reflection of cosmic infall, and the associated reorientation of galactic angular-momentum vectors. Since the discovery of the Galactic warp by Burke (1957) and Kerr (1957), there has been a debate as to whether warps are self-consistent intrinsic structures, or externally driven. Kahn & Woltjer (1959) suggested that the Galactic warp was driven by an intergalactic wind, while Lynden-Bell (1965) suggested that a warp can be an intrinsic structure. The latter proposal was shot down by Hunter & Toomre (1969). After the discovery of dark matter, Toomre (1983) and Dekel & Shlosman (1983) argued that warps might after all be intrinsic structures, and Sparke & Casertano (1988) developed this proposal to the point that it became very attractive. Recently Nelson & Tremaine (1995) and Binney, Jiang & Dutta (1998) have demonstrated that the Toomre–Dekel proposal, as elaborated by Sparke & Casertano, is not viable. The flaw in the approach of Sparke & Casertano is the treatment of the dark halo as a rigid, unflexing thing. The semi-analytic work of Nelson & Tremaine and the numerical simulations of Binney et al. demonstrate that a dark halo responds rapidly to any warp in an embedded disk in such a manner that warps predicted to endure for ever by Sparke & Casertano actually wind up within a few dynamic times.
Binney et al. did not demonstrate that intrinsic warps are impossible, but only that any long-lived warp would have to be a manifestation of a cooperative distortion of both disk and halo. However, a priori it is not clear that such configurations exist, and extensive numerical experimentation by several groups has failed to find one. Hence, the theoretical case for intrinsic warps must be considered at best doubtful. Moreover, new observations (Shang et al. 1998) of the classic example of an isolated galaxy with an integral-sign warp, NGC 5907, have shattered the observational case for the existence of warps in isolated galaxies: NGC 5907 possesses both a dwarf satellite \( \sim 37 \text{kpc} \) from its centre, and an elliptical ring of luminosity that probably contains the debris of another, now shredded, companion.

What is the theoretical status of externally driven warps? The original proposal of Kahn & Woltjer (1959) is not viable because it relies upon a massive, subsonic wind past the Milky Way, for which there is no evidence. Similarly, proposals involving magnetic fields (Battaner, Florido & Sánchez-Saavedra, 1990) are for various reasons not in serious contention. An idea that remains plausible is that warps are a response to the accretion by a galaxy of material laden with angular momentum about an axis that is inclined to the galaxy’s original spin axis (Binney & May, 1986; Ostriker & Binney, 1989). Jiang & Binney (1999) followed the dynamics of a disk embedded in a live halo by decomposing the disk into a series of massive rings that interact gravitationally with one another and with the 100000 particles that represent the halo. The disk is exponential out to \( R = 3.5R_d \) and is then smoothly tapered to zero surface density at \( R = 4R_d \). The halo initially has ten times the mass of the disk and ensures that the overall rotation curve is very nearly flat out to \( 5R_d \). The accretion of material by the halo is simulated by injecting particles into a torus of major radius \( 8.9R_d \) whose spin axis is inclined by \( 15^\circ \) to the original spin axis of the disk. In response to the accretion, the disk develops an integral-sign warp that carries the outermost ring \( \sim 0.3R_d \) above and below the plane of the innermost ring. Hence the warp is very comparable in magnitude to the warp of the Milky Way. This simulation shows very clearly that the warp is essentially a halo phenomenon: accretion causes the outer halo to tip with respect to the inner halo. The disk largely acts as a tracer of the internal dynamics of the halo.

How much infalling matter is needed to generate a warp? In this simulation, the reorientation of the galactic angular momentum is driven by the crude expedient of adding mass to a tilted annulus of fixed radius. This procedure is well defined and easy to describe, but it exaggerates the mass of infalling material that is required to slew a galaxy’s angular momentum by a given amount because neither the angular-momentum per unit mass of the infalling material, nor the angle between its spin axis and the galaxy’s original spin axis increases with time, as they would in a more realistic situation. Indeed, if the simulation were continued for longer, the galaxy’s angular momentum would everywhere become parallel to the symmetry axis of the torus, and the warp would fade away. In the real world, by contrast, the angular momentum vector of infalling material will be constantly shifting its direction, and, moreover, less and less material will be required to import a given quantity of angular momentum. Hence the simulation’s plausibility hinges on whether the rate of angular-momentum slewing in it is plausible, rather than on the likelihood that a galaxy will accrete as much material at \( \sim 10R_d \) as is crudely assumed.
Several authors have studied how tidal interactions endow protogalactic regions with angular momentum at early times (e.g. Heavens & Peacock 1988) and these studies are generally in good agreement with numerical simulations (Barnes & Efstathiou 1987). Ryden (1988) and Quinn & Binney (1992) investigated the rate at which the direction of infalling angular momentum should slew by studying the angular momenta of individual spherical shells of protogalactic material. Quinn & Binney found that the angular momenta acquired by shells that differ in radius by a factor 2 have a clear tendency to be antiparallel. Moreover, the angular momentum per unit mass of a shell rises strongly with radius, with the consequence that the net angular momentum of a galaxy tends to be aligned with the angular momentum of the most recently accreted shell. These two results together imply that the net spin axis of a halo tends to slew through more than 90° in the time required for the radius of the currently accreting shell to double. This time depends on the cosmology and the initial density profile (e.g. Fillmore & Goldreich 1984). For critical cosmic density, $\Omega = 1$, it is typically comparable to the current Hubble time and the halo’s spin axis is likely to slew by $\gtrsim 7°$ in the 0.9 Gyr that the Jiang & Binney simulation lasted.

4. Infalling satellites

It has long been recognized that the Magellanic Clouds are spiralling into the Milky Way. Dynamical models of this process (Murai & Fujimoto 1980; Gardiner et al. 1994; Moore & Davis, 1994; Lin et al. 1995) have been successful in predicting the proper motions of the Clouds, which have now been measured to reasonable accuracy (Jones, Klemola & Lin, 1994; Kroupa & Bastian, 1997). These models are based on the assumption that the Magellanic Stream comprises material that has been tidally stripped out of the Clouds. Hence the success of these models implies that as the Clouds sink deeper into the Galactic halo, a polar ring will form. Since there will be more angular momentum in this ring than there is in the Galactic disk, the orbit of the Clouds constitutes direct evidence for the accretion of mis-aligned angular momentum.

Ibata, Gilmore & Irwin (1994) discovered that the Galaxy has a much nearer satellite than the Clouds, namely the Sagittarius Dwarf galaxy, that is almost hidden from us by the Galactic centre even though it is at a Galactocentric distance of only 16 kpc. Like the Clouds, the Sgr Dwarf is in a nearly polar orbit (Ibata et al. 1997), but the poles of the two orbits make an angle of $\sim 90°$ with one another. It seems that the Dwarf’s orbit has a remarkably short period $\sim 1$ Gyr (Ibata & Lewis 1998).

On such a short-period orbit the Dwarf is severely tidally limited by the Galaxy, and there is direct observational evidence that the Dwarf is being tidally shredded: an arc of associated material has now been detected that extends over $\gtrsim 60°$ on the sky (Mateo, Olszewski & Morrison, 1999). Several authors have concluded that a Dwarf that contained only the observed luminous material could not have survived tidal shredding for a Hubble time on its present orbit. By enveloping the observed dwarf in a rather homogeneous cloud of dark matter, Lewis & Ibata (1998) were able to construct a model of the Dwarf which retained 46% of its original mass after a Hubble time on its present orbit.
Jiang & Binney (this volume) ask how the Dwarf could have got into its present configuration: galaxies are not likely to form in regions where an external tidal field is strong, because the field would shear away protogalactic material and prevent it accumulating locally. Moreover, the configuration proposed by Lewis & Ibata is finely tuned in the sense that the dark halo has to be very homogeneous and sharp-edged. For these reasons it seems likely that the Dwarf was formed at a considerable distance from the Milky Way, and has subsequently moved onto its present tight orbit by one of two mechanisms. Zhao (1998) suggested that the Dwarf was recently scattered onto its orbit by an encounter with the Clouds. The problem with this proposal is the softness of the potentials of the Dwarf and the Clouds relative to the large velocity of any encounter between them: the required scattering is through a substantial angle. Dynamical friction is the other mechanism that could have moved the Dwarf onto a short-period orbit. The problem here is that the present mass of the Dwarf, even including the Lewis & Ibata dark halo, is too small ($\sim 10^9 \, M_\odot$) for dynamical friction to be effective.

Jiang & Binney combine N-body simulations, in which both Dwarf and Galaxy are live systems, with a semi-analytic model, that incorporates dynamical friction and tidal limitation, to explore the rather large parameter space of possible Dwarf histories. They identify a one-parameter family of initial configurations in which the Dwarf starts out at ever greater Galactocentric distances. In the most distant initial configuration explored, the Dwarf starts from $R = 250 \, \text{kpc}$ as an object of mass $10^{11} \, M_\odot$, largely in the form of a dark halo with central velocity dispersion $\sim 50 \, \text{km} \, \text{s}^{-1}$ and roughly constant circular speed. At the other extreme, the Dwarf starts from $R \approx 60 \, \text{kpc}$ with mass $\sim 1.4 \times 10^{10} \, M_\odot$. The off-axis angular momentum that the Dwarf brings to the Galaxy, which varies by a factor $\sim 30$ between extreme configurations, would have a pronounced effect of the Galactic warp at the upper end of the range. Hence, it should be possible to constrain the history of the Dwarf by modelling the combined effect of the Dwarf and the Clouds on the outer disk.

5. Conclusions

From the kinematics of M31 we know that the Local Group has yet to virialize. Hence, there is an a-priori expectation that out towards the edges of the Local Group there is a reservoir of material from which M31 and the Galaxy are accreting at a significant rate.

There is a real possibility that this reservoir can be traced through high-velocity clouds (HVCs). This proposition is controversial because the HVCs form a heterogeneous group. Some are clearly associated with M31, the Magellanic Clouds, and other, lower-mass systems such as Phoenix (St-Germain et al, 1999). Others are material in the Galactic halo, but one can identify substantial subset of HVCs that are most naturally interpreted as rather massive objects of order 1 Mpc from the Galaxy that have yet to fall to the centre of the Local Group. These clouds may together contain $\sim 10^{10} \, M_\odot$ of HI and enable the Galaxy to accrete HI at a rate of $\sim 0.8 \, M_\odot \, \text{yr}^{-1}$ and dark matter at a rate ten times higher.

Currently we know of no viable mechanism by which warps could survive long in an isolated galaxy, and there is no longer observational support for the
proposition that warps exist in isolated galaxies. It seems likely that warps are
a manifestation of a galaxy accreting material whose net angular momentum is
not parallel to that of the galaxy. To generate a typical warp, off-axis angular
momentum must be accreted at such a rate that the spin axis of the inner galaxy
slewed by $\sim 10^\circ$ per Gyr.

Observations of the Magellanic Stream and the Sgr Dwarf Galaxy tell us
that the Milky Way is certainly accreting off-axis angular momentum. Whether
this accretion is fast enough to slew the inner Galaxy’s spin axis by $\sim 10^\circ$ per
Gyr depends on how much dark-matter is being accreted alongside the observed
luminous matter. If there is 10 times as much dark as luminous matter, it should
be possible to explain the Galactic warp, although the very peculiar morphology
of the Galactic warp has yet to emerge from a model of Galactic accretion.

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