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Gas accretion onto galaxies: models vs observations

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Gas accretion is a vital support for galaxy evolution and the feeding of star formation. In recent years, the study of gaseous haloes surrounding disk galaxies has shown the presence of gas complexes, analogous to the galactic High-Velocity Clouds, that can be direct evidence of gas accretion. However, the accretion rates estimated from these features consistently give values, which are one order of magnitude lower than what is needed to feed the star formation. This problem can be overcome if most of the accretion is "hidden" and visible only indirectly through the effects it has on the kinematics of the halo gas. In this second scheme, the gas expelled from the disk through galactic fountains sweeps up ambient gas causing it to accrete. This model provides an explanation for the missing gas accretion and also reproduces the peculiar kinematics of the halo gas, in particular the vertical rotation gradient.

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1. Introduction

Galaxies form and evolve through the acquisition of gas from the surrounding intergalactic space however the mechanisms guiding this process are still largely unknown. A major effect of gas accretion onto galaxies is Star Formation. In the Milky Way the Star-Formation rate (SFR), at least in the solar neighbourhood, has been remarkably constant over the last 10 Gyrs (Twarog 1980; Binney et al. 2000). Given that the current SFR would exhaust the gas in the solar neighbourhood in a couple of gigayears, it seems that the gas consumed by star formation in a disk galaxy like the Milky Way must be replaced by accretion. Steady accretion of metal-poor gas is also required to explain the discrepancy between the observed stellar metallicity distribution in the solar neighbourhood and the prediction of closed-box chemical evolution models (Tinsley 1981; Matteucci 2003).

The star formation history of the Milky Way and star-forming galaxies in general differ substantially from the history of the global star-formation density, derived using SFR tracers such as UV or IR luminosities (e.g. Hopkins & Beacom 2006). The universal SFR shows a decline of a factor 10 from redshift about 1 to now, and it appears fairly constant beyond redshift 1. Cosmological surveys are however dominated by large galaxies such as ellipticals and SOs at high redshifts, i.e. galaxies that belong to the so-called red-sequence and that stopped forming stars at an earlier epoch than the less massive blue-sequence galaxies. Indeed the breakdown of the SFR density in bins of galaxies with different masses shows that Milky-Way type galaxies have a very slowly declining SFR and spirals of later type even a slowly rising SFR (Panter et al. 2008). For Milky-Way type galaxies we can assume that the current SFR is about $2 M_{\odot}\,\mathrm{yr}^{-1}$, thus a roughly similar rate of gas accretion is required and should be detected in the local Universe.

A further piece of evidence for gas accretion comes from observations of the so-called Damped Lyman Alpha (DLA) systems, long recognized to be the analogues at high redshift of the local population of (gas-rich) spiral galaxies. A comparison between DLA studies and local galaxy surveys such as HIPASS (Barnes et al. 2001) indicate that the amount of neutral gas in galaxies has not changed significantly throughout the Hubble time (Zwaan et al. 2005), at most it has declined by a factor 2 between redshift 4 and now. This is consistent with the fact that the SFR in the Milky Way has not changed substantially over the same timeframe. The behaviour of the gas mass in galaxies is remarkably different to that of the stellar mass as between $z = 4$ and now the stellar mass has built up by a factor more than 10 in a galaxy like the Milky Way.

2. Gas accretion from minor mergers

Is the postulated accretion detected in the local Universe? A number of local galaxies show signs of interaction with gas-rich dwarf companions or have peculiar kinematical features that can be revealed in neutral gas (HI) surveys such as tails or large infalling gas complexes. All these systems can be considered as minor mergers at different stages. Some have obvious optical companions with HI tails and bridges indicating that an interaction is taking place, others have no visible companions but peculiar features in their HI structure and kinematics, which are reminiscent of interactions (Sancisi et al. 2008). In these minor mergers the companions have HI masses less than 10% of the main galaxy. The Milky Way and the Magellanic Clouds are in this class of phenomena and the Magellanic Stream (Bruns et al. 2005) is the gas component (about $1.2 \times 10^8 M_\odot$) probably destined to be accreted. At advanced stages of the interaction-accretion process the accreting dwarf may be no longer visible or easy to identify unambiguously. An example is M 101 (Fig. 1), where a large HI complex of about $2 \times 10^8 M_\odot$ has been found falling in with velocities of up to 150 km/s with respect to the galaxy disk (van der Hulst & Sancisi 1988). This is suggestive of a collision with a dwarf companion that may have gone through the disk leaving the hole observed in Fig. 1 (bottom right).

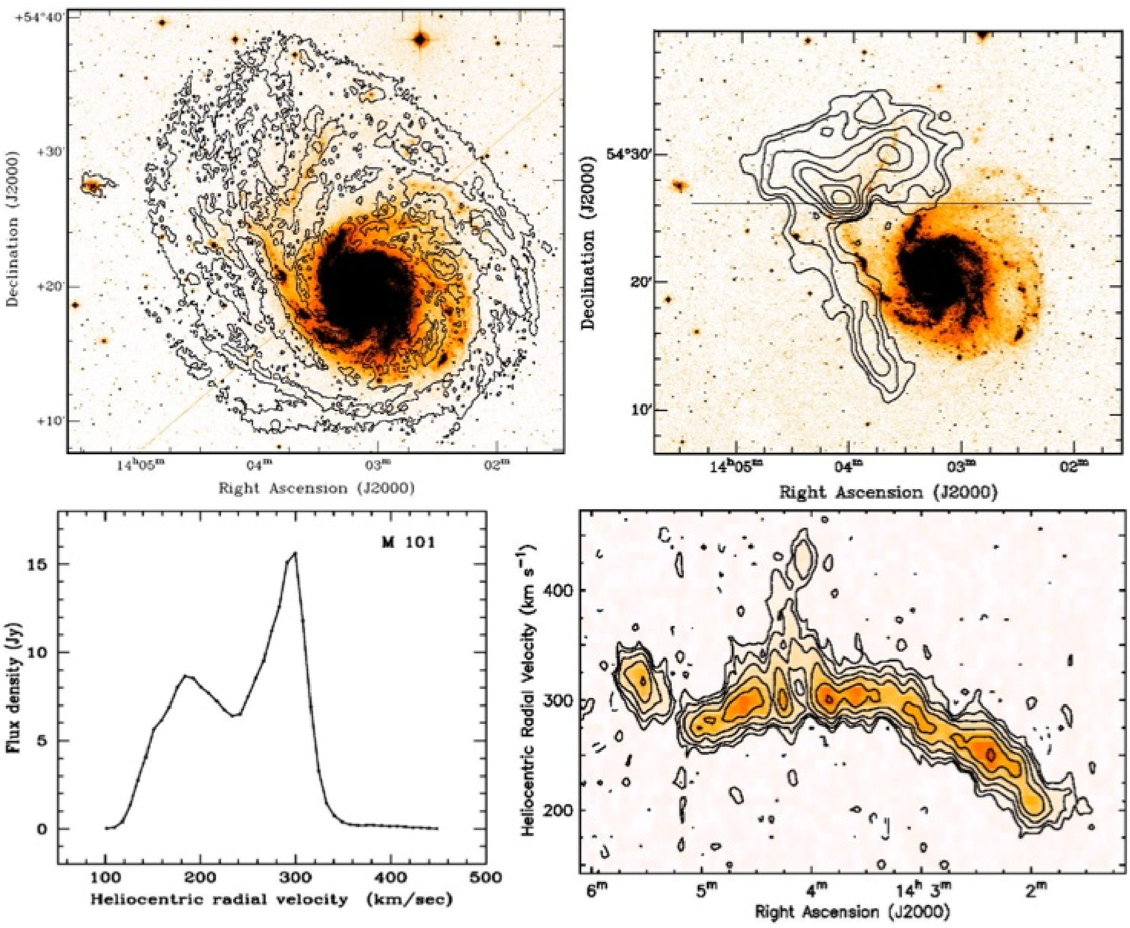

Figure 1: Top left: total HI map for M 101 (contours) overlaid on a DSS image. Top right: high-velocity gas complex (contours) overlaid on the optical image. Bottom left: global HI profile. Bottom right: Position-velocity diagram at constant declination (see horizontal line in top right panel) showing the high-velocity HI complex. From Sancisi et al. 2008.

A first estimate of the accretion events in local galaxies has been made using the sample of galaxies provided by WHISP (van der Hulst et al. 2001). From an inspection of this sample about 25% of 300 spirals and irregulars show evidence of minor interactions. If 25% of these field galaxies are undergoing now or have undergone in the recent past some kind of tidal interaction and we assume lifetimes of the observed features of about 1 Gyr, given that the gas features have HI masses of order $10^{8-9} M_\odot$, the mean accretion rate from these interactions will be around $0.1-$

$0.2\,M_\odot\,\mathrm{yr}^{-1}$. Thus the measured accretion rate is about an order of magnitude lower than the SFR.

3. Halo gas in spiral galaxies

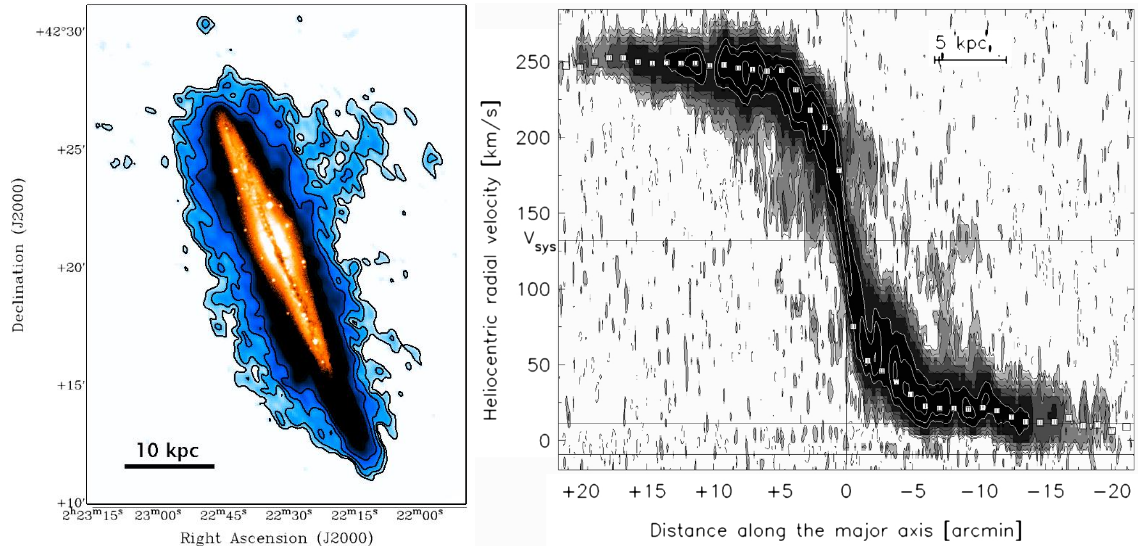

Figure 2: Two methods of detecting extra-planar gas. Left: total H I map (blue + contours) for the edge-on galaxy NGC 891 overlaid on the optical image (orange) (data from Oosterloo, Fraternali & Sancisi 2007, obtained with the Westerbork Synthesis Radio Telescope). The extra-planar gas is clearly separated on the sky, it surrounds the whole galactic disk with a filament extending up to 20 kpc. Right: position-velocity diagram along the major axis of the intermediate inclination galaxy NGC 2403 (from Fraternali et al. 2001). The extra-planar gas is kinematically separated from the disk gas; it is seen as a faint component rotating more slowly than the disk (white dots = disk rotation curve).

The detection of the extra-planar gas in nearby galaxies is a difficult task given the low surface brightnesses involved. In the last decade or so, deep HI observations have been collected for about 15 galaxies (see Table 1, which also includes the Milky Way). For edge-on galaxies the halo gas is spatially separated from the disk gas, whilst for galaxies seen at intermediate inclinations it can be separated thanks to its distinct kinematics. Fig. 2 shows the two ways of detecting extra-planar HI. The total HI map of NGC 891 (left) shows an extended H I halo with a mass of $1.2\times10^9\,M_\odot$ (Oosterloo, Fraternali & Sancisi 2007). On the right panel of Fig. 2, the position-velocity plot along the major axis of NGC 2403 shows a broad component of gas at velocities lower than the rotation of the disk (called the "beard").

The main kinematic feature of extra-planar gas is its decreasing rotational velocity with increasing height above the plane, it is said to be "lagging" behind the disk gas (Matthews & Wood 2003). Such a velocity gradient has been estimated for only a few galaxies (Table 1, column 9) and yet it is an important constraint for models of extra-planar gas formation (see Section 5). The presence of this gradient is also the main reason why extra-planar gas can be detected in galaxies which are not edge-on. Extra-planar gas is possibly ubiquitous and it is also observed in the ionised phase. Optical studies of nearby edge-on galaxies show that roughly half of them have extended

Table 1: Physical properties of extra-planar gas in spiral galaxies

Galaxy	Type	incl	v_{flat}	$M_{HI_{halo}}$	$M_{HI_{tot}}$	SFR	Acc. rate	Gradient[a]	Ref.
		(°)	(km/s)	($10^8 M_\odot$)	($10^9 M_\odot$)	($M_\odot$/yr)	($M_\odot$/yr)	(km/s/kpc)	
Milky Way	Sb	-	220	~ 4	4	$1-3$	$\approx 0.2^b$	-22^c	(1,2,3)
M 31	Sb	77	226	> 0.3	3	0.35	-	-	(4,5)
M 33	Scd	55	110	> 0.1	1	0.5	0.05^d	-	(6,7)
M 83	Sc	24	200	0.8	6.1	$1.1-2.4$	-	-	(8)
NGC 253	Sc	~75	~185	0.8	2.5	> 10	-	-	(9)
NGC 891	Sb	90	230	12	4.1	3.8	0.2	-15	(10)
NGC 2403	Scd	63	130	3	3.2	1.3	0.1	$\sim -12^e$	(11)
NGC 2613	Sb	~80	~300	4.4^f	8.7	5.1	-	-	(12)
NGC 2997	Sc	32	226	1.4	8.0	5	1.2	$18-31^e$	(13)
NGC 3044	Sc	84	150	4	3	2.6^g	-	-	(14)
NGC 4559	Scd	67	120	5.9	6.7	0.6^g	-	$\sim -10^e$	(15)
NGC 5746	Sb	86	310	~ 1	9.4	1.2	0.2^h	-	(16)
NGC 5775	Sb	86	200	-	9.1	7.7^g	-	-8^i	(17,18)
NGC 6503	Scd	75	113	$2-4^l$	1.9	0.18	-	$\sim -13^e$	(19)
NGC 6946	Scd	38	175	$\gtrsim 2.9$	6.7	2.2	-	-	(20)
UGC 7321	Sd	88	110	$\gtrsim 0.1$	1.1	$\sim 0.01^m$	-	$\gtrsim -25^e$	(21)

[a] Gradient in rotation velocity with height (from the flat part of the rotation curve); [b] from complex C and other clouds with known distances without correction for the ionised fraction; [c] extrapolated from the inner 100 pc (Levine et al. 2008); [d] from the H I mass in Grossi et al. without their correction for the ionised fraction; [e] not measured directly: derived from the average lag divided by an estimate of the halo thickness; [f] from the sum of the various extra-planar clouds; [g] calculated from the FIR luminosity using the formula in Kewley et al. 2002; [h] from the counter-rotating cloud using an infall time-scale of 1×10^8 yr; [i] estimated using optical lines (Heald et al. 2006a); [l] from the models of Greisen et al. (2009), average between central and outer parts; [m] SFR of only massive stars $> 5 M_\odot$. References: (1) Kalberla & Dedes (2008); (2) Wakker et al. (2007); (3) Levine et al. (2008); (4) Thilker et al. (2004); (5) Walterbos et al. (1994); (6) Reakes & Newton (1978); (7) Grossi et al. (2008); (8) Miller, Bregman & Wakker (2009); (9) Boomsma et al. (2005); (10) Oosterloo et al. (2007); (11) Fraternali et al. (2002); (12) Chavez et al. (2001); (13) Hess et al. (2009); (14) Lee et al. (1997); (15) Barbieri et al. (2005); (16) Rand & Benjamin (2008); (17) Irwin et al. (1994); (18) Heald et al. (2006a). (19) Greisen et al. (2009); (20) Boomsma et al. (2008); (21) Matthews & Wood (2003).

layers of diffuse ionised gas (Rossa & Dettmar 2003) and with similar kinematics to the H I (Heald et al. 2006b).

4. Accretion from halo gas

The strategy to estimate gas accretion is to look for gas components (usually at very anomalous velocities) which are incompatible with an internal origin (galactic fountain, Shapiro & Field 1976). The large majority of the extra-planar gas studied so far has actually a very regular kinematics that follows closely the kinematics of the disk (see for instance the p-v diagram for NGC 2403, right panel of Fig. 2). This points to a tight connection between disk and halo components.

The first features that deserve attention in the search for gas accretion are H I filaments. NGC 891 has a long massive filament ($M_{\rm HI} \sim 1.6 \times 10^7\, M_\odot$) extending up to about 20 kpc from the plane of the disk (Fig. 2). NGC 2403 also has a filament with a similar H I mass located in projection outside the bright optical disk, partially visible in the p-v diagram in Fig. 2. They are both very similar to Complex C in our Galaxy. The energy needed to form these filaments assuming that they come from the disk through a galactic fountain is of the order $\sim 1 \times 10^{55}$ erg, i.e. about 10^5 supernovae. A second type of feature that has been found in these new deep surveys are clouds at very anomalous velocities that end up in the region of counter-rotation. These clouds cannot be produced in any kind of galactic fountain and they are most likely direct evidence of gas accretion.

From the above structures we can estimate the rate of gas accretion by assuming typical infalling times of few $\times\, 10^7 - 10^8$ yr. The resulting rates are shown in Table 1 (column 8), they are typically of the order $0.1\, M_\odot\, {\rm yr}^{-1}$ and generally 1 order of magnitude lower than the SFRs. These directly observed accretion rates include only H I, and they should be corrected for helium and possibly ionised gas fractions. However, it appears difficult to reconcile them with the rates of star formation (column 7, Table 1).

5. Gas accretion induced by galactic fountain

The result that the rate of gas accretion onto galaxies which is directly observed is much lower than expected implies that most of the accretion should be somewhat "hidden". I describe here possible indirect evidence of this missing gas accretion, provided by the rotation velocity gradient of the extra-planar gas. The steepness of this gradient is not reproduced by galactic fountain models (e.g. Fraternali & Binney 2006; Heald et al. 2006b) as they tend to predict shallower values (a factor half or less). Fig. 3 highlights this problem for NGC 891. The points are rotation velocities derived at heights $z = 3.9$ kpc and $z = 5.2$ kpc from the plane. Clearly the fountain clouds in the model rotate too fast (have a larger angular momentum) than the extra-planar gas in the data.

How can the fountain clouds loose part of their angular momentum? Fraternali & Binney (2008) consider the possibility that fountain clouds sweep up ambient gas as they travel through the halo. In this scheme ambient gas condenses onto the fountain clouds, these latter grow along their path through the halo and eventually fall down into the disk. If the ambient gas has relatively low angular momentum about the z-axis then this process produces a reduction in the angular momentum of the fountain gas. The only free parameter of the model is the accretion rate, which is tuned to reproduce the rotation curves of the extra-planar gas. Remarkably, the required gas accretion rate turns out to be very similar to the SFR. For NGC 891 we found a best-fit accretion rate of about $3\, M_\odot\, {\rm yr}^{-1}$ (see the blue curves in Fig. 3) and for NGC 2403: $0.8\, M_\odot\, {\rm yr}^{-1}$. In NGC 2403, this model is also able to reproduce the observed radial inflow of the halo gas (Fraternali & Binney 2008).

One implication of the above fountain+accretion model is that it predicts that most of the extra-planar gas is produced by the galactic fountain and only a small fraction (about 10%) is extragalactic. This is in agreement with the metallicity of the IVCs and the clear links between anomalous velocity clouds and star forming regions (e.g. Boomsma et al. 2008). A second im-

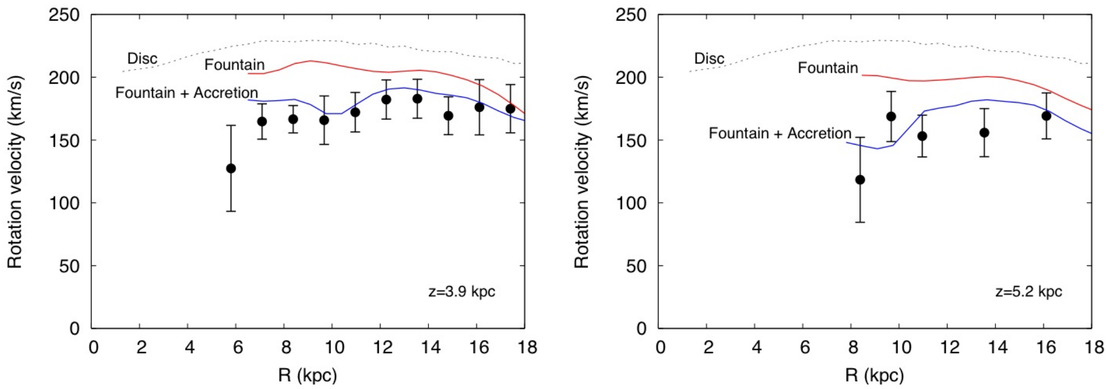

Figure 3: Indirect evidence for gas accretion. Rotation velocities (black points) of the H I extra-planar gas in NGC 891 at 3.9 kpc (left) and 5.2 kpc (right) from the plane compared to the disk rotation curve (dotted line) and predictions from two models: a pure galactic fountain model (red line above) and a model where the fountain clouds sweep up and accrete ambient gas during their passage through the halo (blue line below). The accretion rate required to produce this fit is $\sim 3 M_{\odot}\,\mathrm{yr}^{-1}$, very similar to the star formation rate of NGC 891 (from Fraternali & Binney 2008).

plication is that it does not require that the accreting gas is in any particular phase but only that its angular momentum about the z-axis is less than about half the angular momentum of the disk material. Finally, this model predicts an accretion rate of the order of the SFR and in general, proportional to the supernova rate. Interestingly, this appears to be a general requirement for galaxies throughout the Hubble time as it reconciles the observed cosmic star formation history with the gas mass in galaxies at low and high redshifts (Hopkins, McClure-Griffiths & Gaensler 2008).

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