Infall of gas in galaxies and triggered star formation

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30 November 2002

Abstract. While the importance of merging, accretion, and infall processes in determining galactic evolution is well established both theoretically and observationally, details on how such processes are taking place nowadays even in our own Galaxy are still relatively poorly known, especially due to large remaining uncertainties on the location and origin of high velocity clouds. In this paper we focus on the possible role that galactic outflows and gas infall may have on directly triggering star formation in the halo and in galactic disks. While compelling evidence has been accumulating in recent years suggesting that some level of star formation directly triggered by outflows is very likely to exist in the halo of some galaxies, the evidence for star formation dynamically triggered by infall is far more elusive due to confusion with other, more efficient large-scale star forming mechanisms operating in the galactic disk. Despite of increasingly realistic simulations of the gas circulation betwen the gas and the halo and of high velocity cloud impacts on galactic disks, the efficiency of star formation directly triggered by such impacts remains an open question.

Keywords: infall, large-scale star formation, galactic outflows, high velocity clouds

1. Infall: need and evidence

Ample evidence exists nowadays on the importance of aggregation processes in the buildup and evolution of structures in the Universe (e.g. Bertschinger (1998)). The observation of protogalactic clumps at high redshifts, and the remarkable differences in galaxy morphologies between the early universe and the local one (Ferguson et al. (2000), Venemans et al. (2002)), testify to the importance of mergers in progressively giving shape to the present-day population of galaxies (Freeman & Bland-Hawthorn (2002), Keel (2002)). Hierarchical merging, by which dwarf galaxies are accreted by larger ones, has been recognized to play an important role in the formation and evolution of galactic haloes up to the present day, most notably in the case of our own Milky Way (e.g. Unavane et al. (1996), Johnston (1999), Helmi & de Zeeuw (2000), Bullock et al. (2001), Palma et al. (2002)).

In the context of these aggregation processes, we can regard the infall of gas on galactic disks as the lower end in the accretion hierarchy. Extended infall of external gas on galactic disks is needed by current galactic evolution models as a way to maintain star formation rates similar to the presently observed ones in normal spirals (Takeuchi &

Hirashita (2000), Semelin & Combes (2002)), as well as to explain the observed patterns in the chemical evolution of the Milky Way (e.g. Dwek (1998), Chiappini et al. (1997), Wakker et al. (1999), Chiappini (2002), Geiss et al. (2002)) that require a continued supply of low metallicity or even primordial gas. At least to some extent, the observational counterpart of this gas accretion stream is likely to be linked to the existence of High Velocity Clouds (HVCs) observed in ours and other galaxies (see reviews by Wakker & van Woerden (1997), Wakker et al. (1999)). However, even four decades after their discovery, the characteristics, origin, and role of high velocity clouds in the context of galaxy evolution are far from being well established. In particular, their ability to provide with the needed amount of gas at sufficiently low metallicity, and their possible role in shaping the gaseous layer of galactic disks, possibly even directly triggering star formation, are still unclear.

2. Primordial infall vs. galactic fountain

The external origin of HVCs as leftovers of the building blocks of the local group was proposed shortly after their discovery in the early 1960s (Oort (1970)). A related scenario is the tidal stripping and further accretion of low-metallicity gas from dwarf irregular companions, which in the case of the Magellanic Stream is directly observed (Matthewson et al. (1974), Putman et al. (1999), Wakker et al. (2002)). On the other hand, the dynamical picture of the interstellar medium developed in the 1970s, with the recognition of the important role played by localized events such as supernova explosions and winds from massive stars (McKee & Ostriker (1977)), led to the realization that the circulation of gas between the disk and the halo should be a natural consequence of the energetic processes taking place in galactic disks, thus favoring the interpretation of infall as gas returning to the disk. In the *galactic fountain* scenario (Shapiro & Field (1976), Bregman (1980), Shapiro & Benjamin (1991), Kahn (1994), de Avillez (2000)), gas infall, and particularly HVCs, result from thermal instabilities in a hot gaseous halo that is continuously replenished with hot gas produced by supernovae and stellar winds in the disk. With a variety of refinements that take into account factors such as the clustering of the main sources of hot gas in galactic disks (Ikeuchi (1988), Norman & Ikeuchi (1989), Li & Ikeuchi (1990), de Avillez & Berry (2001)), the galactic fountain is an integral part of current global models of the interstellar medium (de Avillez (1999)). From the observational point of view, the outgoing component of the galactic fountain has been studied in a number of nearby edgeon galaxies, in particular those having central starbursts, which display outflows of hot gas directly observable at different wavelengths (Lehnert & Heckman (1995), (1996), and the review by Dahlem (1997)); M 82 is probably the best documented example (e.g. Lehnert et al. (1999)).

While it is well established that the properties of gaseous halos are correlated with the star forming activity in the underlying disk (Dahlem (1997)), thus supporting the link between both, analogous correlations seem to exist between the high velocity HI masses of external galaxies (interpreted as HVC) and their star forming activity as traced by the integrated far-infrared flux (Schulman et al. (1994), (1996)), providing further evidence for the link between HVCs and the galactic fountain.

Theoretical developments supporting the viability of the galactic fountain model, the determination of upper limits to the distances of some high and, especially, intermediate velocity clouds placing them within a few kpc from the Sun, and the determination of non-primordial metallicities by means of their detection in absorption against background probes (Wakker (2001)) favored the interpretation of HVCs as components of the galactic halo during the 1980s and 1990s. However, interest in HVCs as possible members of the local group unrelated to the Milky Way has been recently stirred by the work of Blitz and collaborators (Blitz et al. (1999), Blitz (2002)), leading to a reassessment of the arguments for and against an origin of HVCs in the galactic fountain. Arguments in favor of an extragalactic origin are the realization of the importance of accretion of dwarf galaxies in understanding galaxy evolution, the prediction by CDM-based structure formation models of a low-mass tail in galaxy groups represented by dwarf irregulars and possibly HVCs, the subsolar metallicity of most HVCs for which a reliable metallicity determination is available (Wakker et al. (1999), Wakker (2001), Gibson et al. (2001a), Sembach et al. (2002)) that could account for the low-metallicity gas infall required by galaxy evolution models as noted in the previous Section, and the identification of a population of compact HVCs with kinematical properties apparently relating them to the Local Group rather than to the Milky Way. The evidence is far from unambiguous however, as discussed by Gibson et al. (2001b), (2002), and a definitive conclusion is severely hampered by the very limited data on metallicities, and especially distances, existing so far. Intense observational efforts currently underway trying to detect a stellar population associated to the compact, isolated HVCs that lend the strongest support to Blitz et al.'s hypothesis for a Local Group origin have so far produced only upper limits that leave this question unsolved for the time being (Davies et al. (2002), Simon & Blitz (2002)).

3. Outflow/inflow and star formation

The evidence for the exchange of large amounts of gas between the disk and the halo, be it by means of accretion of primordial material or through a galactic fountain-like mechanism, has led to speculations on the possible occurrence of star formation triggered by the dynamical interaction of gas supersonically entering the galactic disk.

3.1. Outflow-triggered star formation in galactic haloes

More recently however, the possibility that gas outflows may also trigger star formation in exotic environments far removed from usual star forming sites such as the giant molecular cloud complexes in the disks of spiral galaxies has been the subject of considerable interest. In our own Milky Way, the existence of high-latitude B-type stars sharing all the characteristics of normal early-type main sequence stars, but lying at distances of the disk too large to have been achieved by formation in the disk and subsequent ejection as runaway (e.g. Brown et al. (1989), Conlon et al. (1992), Hambly et al. (1993), Little et al. (1995)) has led to the suggestion of *in situ* formation, perhaps in instabilities within HVCs or via collisions among them (Dyson & Hartquist (1983), Keenan & Lennon (1984)). Examples of out-of plane (and perhaps even out-of-galaxy!) star formation are now observed or suspected in other galaxies as well, and in such cases the relationship to outflow phenomena seems more clearly established. The best studied case is that of NGC 5128 (Centaurus A), in which a group of blue stars and HII regions has been identified (Graham (1998), Graham et al. (2002)) far from the galaxy in the region where the relativistic jet produced at the center of that galaxy intersects a cloud of HI probably left over from a tidally disrupted companion (Charmandaris et al. (2000)). Other examples have been identified or suggested of AGN-triggered star formation in nearby clouds (Pinkney et al. (1996), van Breugel & Dey (1993)), or in galaxies intersecting the path of the AGN jet (van Breugel et al. (1985), Best et al. (1997), Scannapieco et al. (2000)). Evidence for star formation in galactic haloes possibly triggered by the superwinds produced at the central starburst of NGC 253 has been recently presented by Comerón et al. (2001), (2002). Gerhard et al. (2002) have presented observations of a HII region in the outer halo of NGC 4388, a Seyfert 2 galaxy in the Virgo cluster, suggesting that triggering of star formation in the galactic halo does not need an external source as extreme as the Centaurus A jet. The possible detection of halo B-type stars in M 31 by Hambly et al. (1995) may confirm that star formation in such conditions is possible even in the absence of any energetic central powering engine in the galaxy, with chimneys distributed across the galactic disk pouring streams of hot gas into the halo providing an alternative mechanism.

3.2. Inflow-triggered star formation in galactic disks

The injection of momentum in the halo by jets, starburst superwinds, or chimneys powered by massive stellar association in the disk is likely to have a counterpart in the form of HVCs colliding with the galactic disk. The magnitude of such a momentum injection, and therefore its gas-dynamical consequences on the galactic disk, can be poorly assessed with currently available data given the very limited present knowledge on HVC masses and the sensitivity of the consequences of HVC impacts to the volume filling factors of the different gaseous phases present in the galactic disk. On the other hand, even if star formation were a common consequence of HVC impacts on galactic disks and a mode of star formation much more common than outflow-induced star formation as discussed earlier, presenting unambiguous evidence for it would require convincingly discarding all other much more efficient star formation mechanisms at work in galactic disks. Observational evidence of the violent interaction of high velocity clouds with the galactic disk has been proposed in a number of instances, both galactic and extragalactic (Heiles (1984), Kulkarni & Mathieu (1986), Mirabel & Morras (1990), Meyerdierks (1984), Saito et al. (1992), Stark et al. (1994), Kerp et al. (1996), Rand & Stone (1996), Brosch et al. (1999), Tamanaha (1995), (1997)). In our own Galaxy, a number of studies have suggested that past HVC collisions with the galactic disk may have played an important role in shaping the recent star formation history of the solar neighbourhood (Franco et al. (1988), Comerón & Torra (1992), (1994), Lépine & Duvert (1994), Edvardsson et al. (1995), Cabrera-Caño et al. (1995)), in particular the Gould Belt (Pöppel (1997)). The support for HVC collisions as the cause of star formation in these instances is usually circumstantial, and typically based on the peculiar morphological arrangement of the resulting star forming complexes (an exception to this is Edvardsson et al.'s (1995) support for a HVC impact of the Orion complex, based on the slightly subsolar metallicity of its stellar population which may have resulted from the mixing between solar-metallicity galactic gas and low metallicity HVC gas). In distant regions of our Galaxy and in extragalactic complexes the interpretation is made more difficult by the lack of a three-dimensional picture of the object under study, which can be however obtained in the solar neighborhood, and support for the HVC impact hypothesis is usually based on energetic considerations and the comparison with the required input from supernovae. In recent years interpretations based on localized events more energetic than supernovae, such as Gamma-Ray Bursts, have been seriously considered as possible alternatives (Efremov et al. (1999)).

3.3. Modelling infall-induced star formation

The collision of HVCs with a galactic disk and the properties of the structures formed as a consequence of it have been considered by a number of authors (Tenorio-Tagle (1980), (1981), Tenorio-Tagle et al. (1986), (1987), Comerón & Torra (1992), Santillán et al. (1999)) usually by means of increasingly detailed and realistic numerical simulations, both in terms of spatial resolution and of input physics. Numerical simulations typically follow the evolution of a HVC with an initial size, density, and velocity starting from the time when it encounters either the boundary between the warm HI galactic layer and the hot halo gas, or a density in the former that is high enough to begin producing significant dynamical effects in the HVC. At that stage a shock starts running through the HVC and a shocked layer of dense gas, contributed by both the HVC and the galactic disk, develops. Numerical simulations usually follow the evolution of the gas until some time after all the shock has run across the whole HVC, leaving as a result a dense layer that may eventually become unstable against its own gravity and condense in a large star forming complex (Franco et al. (1988), Comerón & Torra (1994)). Early simulations concentrated on the case of a head-on collision, in which the HVC falls perpendicular to the galactic plane. Comerón & Torra (1992) introduced a velocity component parallel to the galactic plane, finding some important differences with respect to the head-on collision case concerning the evolution of the shocked layer (Comerón & Torra (1994)). Oblique impacts have also been considered by Santillán et al. (1999), and are included naturally in self-consistent 3-D models of the evolution of the galactic HI layer as ejected gas in the halo becomes thermally unstable and returns to the disk (de Avillez (1999), de Avillez & Berry (2001)).

The emphasis of numerical simulations normally lies in the description of the dynamical consequences that the collision has on the galactic layer of warm gas and the way in which different components of the interstellar medium, such as the presence or absence of a large-scale magnetic field, affect the shape and extent of the resulting disturbances. By comparison, relatively little attention has been paid to the initial characteristics of the HVC, for which models have usually explored a rather restricted range of parameters. It is interesting however to note that existing observations, although not determining the initial HVC parameters due to the large distance uncertainty, do impose correlations among them that constrain their possible effects. For instance, although obviously a large and dense HVC should be able to produce a major disturbance in the gas layer near the galactic midplane (Comerón & Torra (1992)), the observed column densities and projected extent on the sky imply that, if HVCs are distant, they are large but not dense, while the opposite is true if they are at short distances. Both cases may however produce a similar outcome in preventing that any significant disturbances reach the proximities of the galactic plane. Recent numerical simulations (Comerón 2003, in prep.) take as input parameters those derived from actual observations of HVC Complex A, a chain of roundish condensations for which a distance fork, and thus limits on size and density, are actually available (Wakker (2001)). The main preliminary result of that work is that the exponential tail in the vertical distribution of HI is in principle a very efficient protection preventing that the effects of a "Complex A-like" impact may be noticeable in the proximities of the galactic midplane. Additional resistance is built in the galactic HI layer by the pressure and tension of the field lines of the large-scale magnetic field, as shown by Santillán et al. (1999), which may even be able to reverse the momentum of the infalling gas and turn the impact into a low-velocity outflow. Nevertheless, several factors may increase the ability of the effects of the collision to penetrate deeper in the galactic HI layer. On one side, the complex structure of HVCs, with hot cores embedded in diffuse haloes (e.g. Wakker & van Woerden (1997), Brüns et al. (2000)) and the large density inhomogeneities that form by instabilities and phase transitions in the shocked layer make more complex the dynamics of the collision, make it possible that individual dense clumps formed at large heights over the galactic plane reach its proximities. On the other, assuming an initially plane-parallel layer of warm HI in hydrostatic equilibrium, as models usually do, is known to be an oversimplification with potentially important consequences on the assessment of the effect of the HVC collision; self-consistent models of the duty cycle of the warm gas and its circulation between the disk and the halo, and actual observations of the large-scale structure of the interstellar medium, suggest a fairly different picture (de Avillez (2000)), with aspects such as the volume filling factor of the different phases of the interstellar gas, their clumpiness, and the vertical structure of the density, pressure, and magnetic field probably having a major importance as well.

4. Concluding remarks

While the importance of infall in galactic evolution is well acknowledged, the details as to how infall takes place and the properties of the

HVCs which most likely are the observational signature of infall are still far from being well established. The distances to HVCs continue to be the single most important factor of uncertainty regarding their origin, their location, their mass, and their effects.

Here we have focused on a particular aspect of the consequences of gas infall on galactic disks, namely the possibility that they directly trigger star formation. While few but compelling examples discovered in the last decade suggest that galactic *outflows* can directly trigger star formation in the exotic environment of the galactic halo, the evidence for infall-induced star formation by HVC impacts on galactic disks is more unclear. Suggestive examples do exist, even in the solar neighborhood, but confirmation is elusive and requires both multiwavelength observations and robust modeling of the observed structures in order to rule out other competing, unrelated possibilities. With the powerful observing facilities at all wavelengths that have entered operations in recent years, and the not less powerful computational resources nowadays available, this is certainly an exciting challenge for observers and modellers alike.

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