Gas and Metal Distributions within Simulated Disk Galaxies

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Abstract. We highlight two research strands related to our ongoing chemodynamical Galactic Archaeology efforts: (i) the spatio-temporal infall rate of gas onto the disk, drawing analogies with the infall behaviour imposed by classical galactic chemical evolution models of inside-out disk growth; (ii) the radial age gradient predicted by spectrophotometric models of disk galaxies. In relation to (i), at low-redshift, we find that half of the infall onto the disk is gas associated with the corona, while half can be associated with cooler gas streams; we also find that gas enters the disk preferentially orthogonal to the system, rather than in-plane. In relation to (ii), we recover age gradient troughs/inflections consistent with those observed in nature, without recourse to radial migrations.

1. Introduction

The infall of gas onto galaxies is a fundamental constituent of any cosmologically-motivated models of galaxy evolution, whether they be classic galactic chemical evolution models (e.g. Lineweaver et al. 2004; Renda et al. 2004) or hydrodynamical simulations (e.g. Kawata & Gibson 2003; Brook et al. 2004). The shape of the metallicity distribution function of a given ensemble of stars can be a powerful tool to constrain the (otherwise, little known) interplay between infalling and outflowing material (e.g. Fenner & Gibson 2003; Pilkington et al. 2012b). In the local Universe, we often associate (rightly or wrongly) this infalling fuel for future star formation with the high-velocity clouds which permeate our halo (e.g. Gibson et al. 2001; Pisano et al. 2004).

Classic chemical evolution models, constrained by both the metallicity distribution function and gradients (abundance and surface density) in the disk, suggest “inside-out” growth of the disk is required (e.g. Chiappini et al. 2001; Fenner & Gibson 2003; Mollá & Díaz 2005; Pilkington et al. 2012a,b). By “inside-out”, we mean a scenario in which the timescale for gas infall onto the disk increases as a function of galactocentric radius; whether this timescale is linear (e.g. Chiappini et al. 2001) or a higher-order parametrisation (e.g. Mollá & Díaz 2005) is less important than the fact that (a) the overall infall rate is (roughly) exponential, and (b) the timescale increases with radius. Fig I shows
one such parametrisation from the chemical evolution model of Renda et al. (2004).

As alluded to above, energetic outflows (driven by a combination of thermal/kinetic energy from supernovae and massive star winds/radiation) also play a critical role in regulating star formation, infall of both fresh and recycled disk material, and setting the chemistry of the resulting system. The heating and chemical profiles of the halo are an ideal place to examine the veracity of one’s feedback scheme through a comparison of the radial profiles of various neutral and ionised species (e.g. H\textsc{i}, O\textsc{vi}, Mg\textsc{ii}) with those observed in nature. We have made significant strides in this area (Stinson et al. 2012), and future works in this series will examine these radial distributions using a statistical sample of cosmological disk simulations in a variety of environments, from field to groups.

The spatio-temporal infall pattern of gas onto the disk and the predicted age gradients within spectrophotometric disk models are touched upon in the following sub-sections. These are each, very much, works in progress, rather than finished products, so we ask the reader to bear that in mind!

2. How Does Gas Get Into Galaxies?

Making use of RAMSES-CH (Few et al. 2012), a new self-consistent implementation of chemical evolution within the RAMSES cosmological adaptive mesh
refinement code (Teyssier 2002), we re-simulate the disk described by Sánchez-Blázquez et al. (2009) and analyse the temporal and spatial infall rates of hot/coronal and cooler/stream gas onto the disk. Our task is a (seemingly) straightforward one: confirm/refute the aforementioned fundamental tenet of chemical evolution, that the gas infall onto simulated disks (in a cosmological context) proceeds in an inside-out fashion.

In the upper-left panel of Fig 2, we show in black (magenta) the inflowing (outflowing) gas flux through parallel (0.5 kpc thick) slabs situated ±5 kpc from the mid-plane (extending to a galactocentric radius of 25 kpc) \(^1\) over the range of time for which the disk could be 'readily' identified (see Sánchez-Blázquez et al. 2009 for details pertaining to the 'disk identification'). In the upper-right panel of Fig 2, we decompose the infalling gas (black curve from the left panel, repeated again here, also in black) into polytropic/hot gas (what we label as 'corona') in red, and non-polytropic/cooler gas (what we label as 'streams') in blue. Within this simulation, (i) the infall from the corona is roughly constant in time, and (ii) at low-redshift, each component accounts for half of the current gas infall. In the lower-left panel of Fig 2, we show the infalling (outflowing) gas flux, again in black (magenta), through a cylinder of radius 25 kpc and height ±5 kpc; i.e., the sum of the fluxes shown here, plus those shown in the upper-left panel of Fig 2, correspond to the real/total accretion rate. For this simulation, the rate of gas infall/inflow entering the disk through the cylinder (i.e., ‘in-plane’ infall/inflow) is fairly negligible. Finally, in the lower-right panel of Fig 2, we show the gas inflow rate through three small ‘holes’ situated ±5 kpc from the mid-plane, at different radii. While noisy, due to the small sampling employed here, we can see the emergence of the fundamental tenet of inside-out disk growth: specifically, the lack of gas accretion at small galacto-centric radii at low-redshift (i.e., a trend for flatter infall profiles at larger radii).

3. Age Gradients

The existence of U-shaped radial age profiles (inferred via radial colour profiles, in consort with stellar population modeling) in disk galaxies (particularly those with so-called Type II surface brightness profiles - i.e., those showing a ‘break’ in the surface brightness) is now well-established (e.g. Bakos et al. 2008; Sánchez-Blázquez et al. 2011; Roediger et al. 2012). Such troughs in age, near the break radius, were found in the exquisite models of Roskar et al. (2008), where the ‘up-bend’ in the age profile in the outer disk was produced by stars that had migrated from the inner parts of the disk; in our cosmological simulation (Sánchez-Blázquez et al. 2009), a similar trough/inflection in the age profile was found at the break radius, where the presence of a warp in the gas disk resulted in a decrease in the volume density and, hence, a ‘break’ in the star formation density. The trough persists, regardless of the presence (or lack thereof) of radial migration (although migration clearly takes place and is critical!).

\(^1\) The choice of ±5 kpc heights is a compromise between being as close to the disk as possible, without being ‘swamped’ by the galactic fountain/re-circulation signal (Gibson et al. 2009; §7).
Figure 2. Upper-left: inflowing (outflowing) gas through slabs ±5 kpc from the mid-plane in black (magenta); Upper-right: inflowing hot/coronal (cooler/stream) gas through the same ±5 kpc slabs in red (blue); Lower-left: inflowing (outflowing) gas through a ±5 kpc high cylinder of radius 25 kpc in black (magenta); Lower-right: inflowing gas through small ‘holes’ ±5 kpc from the mid-plane, at three different radii. See text for details.
Whether U-shaped age profiles are a natural byproduct within classical galactic chemical evolution models is less certain; to that end, we examined the spectrophotometric predictions associated with the same fiducial Milky Way models (Mollá & Díaz 2005; N=28) that were employed in our recent work on the temporal evolution of metallicity gradients in L* galaxies (Pilkington et al. 2012a). In Fig 3, we show predicted present-day mass-weighted age gradients for a Milky Way analog, employing a range of star formation efficiencies (from high efficiency to low efficiency, in going from the top to the bottom curves at small galactocentric radii). We find that within these classical models, which by construct neglect radial migration, U-shaped age profiles are a natural outcome of the infall/star formation prescriptions. It is interesting to note that the position and depth of the trough is sensitive to the adopted star formation efficiency; high efficiencies drive the trough to be (i) positioned at larger galactocentric radii, and (ii) shallower (and vice versa for low star formation efficiencies). In the outer parts of the disk, beyond the minima of the age profiles, the high efficiency models show inverted age profiles, while the low efficiency models show declining age profiles. A more thorough investigation is clearly warranted.

Acknowledgments. Without the help of our collaborators, this work would not have been possible; we thank them all for their ongoing advice and guidance. BKG thanks both Monash and Saint Mary’s Universities for their generous visitor support, and the organisers of what was an incredibly exciting, rewarding, and collegial School and Workshop. BKG, SC, MM and DC acknowledge the support of the UK’s Science & Technology Facilities Council (ST/F002432/1 & ST/H00260X/1). SC acknowledges support from the the BINGO Project (ANR-08-BLAN-0316-01).

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Figure 3. Radial, mass-weighted, age profiles for the fiducial Milky Way models of Mollá & Díaz (2005), for a range of star formation efficiencies. All models possess U-shaped age profiles, with the position and depth of the trough depending upon the adopted star formation efficiency. See text for details.
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