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Outskirts of spiral galaxies

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Abstract. I present an overview of the recent star formation activity in the outer disks of spiral galaxies, from the observational standpoint, with emphasis on the gas content, the star formation law, the metallicity and the stellar populations.

Keywords. galaxies: spiral, galaxies: evolution, galaxies: abundances

1. Introduction

Several galactic properties reach low and often minimum levels in the outer disks, including gas column density, molecular gas content, metallicity, dust content, star formation efficiency, star formation rate surface density and stellar surface density. Peculiar conditions are also encountered in these outer regions of spiral galaxies, such as marginal gravitational stability, long dynamical timescales, and flaring of the gas layer. For these reasons the outskirts of spirals represent exceptional testing sites for models of gas accretion, disk assembly and evolution, and prompt us to address the question whether the star formation physics differs in different regions and environments within galaxies. It is probably fair to state that, while low-level star formation is known to exist in the outer disks of spiral galaxies, as the next section will briefly summarize, we still do not have a clear understanding about why and how this activity proceeds.

2. Star formation

The presence of star-forming regions in the outer reaches of spiral disks, beyond the optical edge defined by the isophotal radius R_{25}, has been known for some time from both optical narrow-band Hα imaging and spectroscopy (Ferguson *et al.* 1998ab, Lelièvre & Roy 2000) and far-UV imaging of extended UV (XUV) disks (Thilker *et al.* 2005, Gil de Paz 2005). When detected, the Hα emission is consistent with the presence of a single or very few ionizing stars in the individual star forming regions, and generally the integrated star formation rates fall in the range $10^{-4} - 10^{-6}$ M$_\odot$ yr^{-1} kpc^{-2}, i.e. up to three orders of magnitude lower than measured in the inner disks. Emission-line searches for outlying H II regions in spiral galaxies (Ryan-Weber *et al.* 2004, Werk *et al.* 2010a) suggested a frequency of 6-10% in nearby systems, and indicated that galaxy interactions can be the primary factor in triggering star formation in the outskirts of galaxies. Similarly, the analysis of GALEX data has yielded a frequency of ∼20%, with interactions frequently associated with the XUV disk phenomenon (Thilker *et al.* 2007, Zaritsky & Christlein 2007, Lemonias *et al.* 2011). Is this outlying star formation predominantly triggered by galaxy interactions, or are there other mechanisms involved? Of course we know that the star formation in the outer disks is connected with the presence of large H I gas reservoirs, with XUV disks being associated with roughly twice the gas mass of non-XUV disks of similar luminosity (Thilker *et al.* 2007). Important progress continues to be made to map these extended H I emission by several independent surveys (LVHIS, GASS, Bluedisk, etc.). The high H I fraction has been linked to bluer optical/UV colors and higher star formation activity in the outer disks (Wang *et al.* 2011), in support of the inside-out evolutionary scenario of galaxy disks.

2.1. *Threshold vs IMF?*

The azimuthally averaged radial profiles of the Hα emission are known to drop near the R_{25} radius, where the H I surface density falls below 3-5 M$_\odot$ pc^{-2} (eg. Kennicutt 1989, Martin & Kennicutt 2001). Hence the notion of sub-critical star formation in the outer disks. The FUV emission typically does not display this behavior. Because of the different stellar mass ranges probed by the Hα (M $>$ 20 M$_\odot$) and FUV (M $>$ 4 M$_\odot$) emission, this discrepancy has been invoked as a potential signature of upper IMF variations (eg. steeper slope or high-mass truncation) in outer disks. However, there are examples of XUV disk galaxies where the Hα radial profile follows the FUV profile quite well, smoothly across the inner-outer disk boundary (Goddard *et al.* 2010, Christlein *et al.* 2010). Thus while it is possible that Hα is a biased star formation tracer at low levels of star formation, these observations do not necessarily imply variations in the IMF. In particular, stochastic effects due to sampling of a small number of ionizing O stars (Boissier *et al.* 2007) and the different stellar age sensitivity of the Hα (t $<$ 10 Myr) and FUV (t $<$ 1 Gyr) emission can explain the apparent discrepancies. The latter argument, in particular, has been used by Koda *et al.* (2012) to explain the relative number counts of Hα- and FUV-emitting clusters in the outer disk of M83 adopting a standard IMF extending up to 100 M$_\odot$, once a constant cluster formation rate constant over the last 70 Myr is assumed.

2.2. *Cluster formation*

While the details of star cluster formation in the outer disks are far from being understood, a popular scenario views star formation as occurring in a generally subcritical (stable) environment, but in gravitationally unstable pockets of higher gas density. It has been shown that outer disks are roughly twice more Toomre-stable than inner disks (Bigiel *et al.* 2010, Barnes *et al.* 2012). That star formation occurs around the critical gas density has been shown by several authors, including Ferguson *et al.* (1998a), Dong *et al.* (2008), and Koribalski & López-Sánchez (2009). The origin of the instabilities can be related to a variety of mechanisms, including the propagation of spiral density waves, gas phase transitions, and variations in the turbulence of the interstellar medium (Schaye 2004, Elmegreen & Hunter 2006). Interactions certainly play a role, too, as in the well-known cases of NGC 4625 and NGC 1512.

Star clusters in the outer disks are often structured in spiral arms and are spatially correlated with H I filaments (Thilker *et al.* 2005, Bigiel *et al.* 2010). The gas densities along these arms can be up to 40% larger than in the inter-arm regions (Barnes *et al.* 2012). The origin of the extended outer arms in the gas distribution, even for isolated disks, is poorly understood and can be related to the environment (eg. minor companion accretion) or it can be intrinsic (eg. due to non-axisymmetric halos, Espada *et al.* 2011).

Hydrodynamic simulations by Bush *et al.* (2008, 2010) have shown that spiral structure can propagate from the inner disks into the outer disks, triggering star formation in overdense regions. In the simulations these are long-lived structures, morphologically resembling the Type I XUV disks defined by Thilker *et al.* (2007). Khoperskov & Bertin (2015) have also shown that large-scale spiral structure can propagate into the outer disks out to very large radii (25 scale lengths) via transfer of angular momentum, with amplitude increasing with galactocentric distance. Shocks develop in the outermost regions due to the supersonic motion of the spiral pattern, which helps explain the star formation activity.

Finally, Herbert-Fort *et al.* (2012) have proposed three modes of cluster formation in outer spiral disks: (i) a low-level cluster formation activity out to $\sim$1.5 R_{25}, triggered by spiral waves extending across the optical edge of the disks; (ii) interaction-induced cluster formation extending throughout the outer disks, and (iii) low-level cluster formation taking place at the edge of the H I distribution, as a result of gas accretion.

2.3. *Star formation histories*

Useful information on the star formation histories of outer spiral disks has been obtained by the combination of near-IR (3.6 and 4.5 μm) Spitzer imaging with FUV GALEX imaging, since this helps to constrain the ratio of old vs. young stars (Bush *et al.* 2014 for the case of NGC 4625, Barnes *et al.* 2014 for the case of M83). It is found that the stellar population colors become bluer with increasing galactocentric distance, in support of the inside-out scenario, but also that the color dispersion increases (Goddard *et al.* 2010, Barnes *et al.* 2011).

Star formation histories in outer disks have been usually modeled as instantaneous bursts (eg. Dong *et al.* 2008, Alberts *et al.* 2011, Bush *et al.* 2014), but also with episodic bursts on timescales of 10^8 yr (Barnes *et al.* 2011, 2013), which helps to explain the color dispersion. The triggering of these bursts can be provided by minor merger or interaction activity, or by the periodic passage of spiral density waves.

More recently López-Sánchez *et al.* (2015) compared the observed Hα equivalent widths and FUV$-$NUV colors of star-forming regions in the outer disk of NGC 1512 with population synthesis models. They concluded that the results are consistent either with the presence of two main star formation events (one occurring 400 Myr ago – at the start of the interaction with NGC 1510 – and one a few Myr ago), or with a combination of a recent burst on top of a continuous star formation activity. The presence of multiple stellar generations in the complexes contained in the outer disk of M83 was also suggested by Thilker *et al.* (2010).

3. Gas

We turn more specifically to the gas content, and at the same time broaden the discussion to include other galactic systems that, like XUV disks, are characterized by inefficient star formation activity (ie. have a low star formation rate per unit mass). In particular, low surface brightness (LSB) galaxies (see Wyder *et al.* 2009) and massive H I-rich galaxies, which have become the subject of several recent radio surveys (GASS: Lemonias *et al.* 2014; Bluedisk: Wang *et al.* 2013; HighMass: Huang *et al.* 2014). The analysis of these systems allows us to study the star formation law at low gas densities, and also to probe processes of gas accretion and disk formation/regeneration. Among the interesting questions that can be addressed are whether we are witnessing a suppression of the star formation activity in these galaxies, or whether these systems are currently experiencing a late accretion of cold gas, leading to a rejuvenation of their disks.

Outer spiral disks are clearly H I-dominated. It is well-known that the molecular-to-atomic ratio decreases rapidly with radius in the inner disks (Schruba *et al.* 2011), and very few detections of molecular gas exist todate for XUV disks (eg. Dessauges-Zavadsky *et al.* 2014 for the case of M63; see also Watson *et al.* 2016). A look at the relation between the gas surface density and the star formation surface density, spatially resolved on kpc scale, shows that the star formation efficiency ($\equiv \Sigma_{\rm SFR}/\Sigma_{\rm gas}$) in outer disks is dramatically smaller than in the inner disks, with gas consumption timescales that are

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on the order of 10^{11} yr, compared to 2-3 Gyr for the inner disks (Bigiel *et al.* 2010). Roychowdhury *et al.* (2015) showed that, while perhaps less extreme, this behavior is shared by other types of H I-dominated systems, including dwarf galaxies and the outer disks of massive, H I-dominated galaxies from the Bluedisk sample. Interestingly, they found a $\Sigma_{\rm SFR} - \Sigma_{\rm gas}$ relation that is very similar to the one observed in spiral outer disks (THINGS sample), regardless of metallicity.

The lower star formation efficiency at low gas densities, which is shared by the different galactic systems mentioned above, still lacks a unique, widely accepted explanation. It has been proposed to be related to the warm-cold phase transition (Schaye 2004, Krumholz *et al.* 2009) or to the transition between subsonic and supersonic turbulence (Kraljic *et al.* 2014). Gas flaring, which starts to become important at the radius where the gas surface density exceeds the stellar surface density, can also explain the drop in star formation efficiency observed in the outer disks (Barnes *et al.* 2012, Elmegreen 2015).

3.1. *Gas accretion*

Cold gas accretion is widely regarded as providing much of the fresh material observed in the galactic outskirts and sustaining the low-level star formation activity. Here I focus on some aspects of the gas accretion phenomenon that appear especially relevant for the structure and evolution of XUV disks and outer spiral disks in general (see Sancisi *et al.* 2008 and Sanchez-Almeida *et al.* 2014 for reviews).

A direct link between cold gas accretion and the XUV disks has been proposed by Roškar *et al.* (2010): outer (warped) disks can originate from gas accreting from outer halos that are misaligned relative to the inner disks. This accretion phase would trigger the star formation we observe in the XUV disks.

Quantified, comparative morphology of XUV disks and H I disks by Holwerda *et al.* (2012) lends support to the idea that cold flows lie at the origin of the UV and H I structures, rather than alternative explanations, such as merger activity and dissociation of molecular hydrogen. Wang *et al.* (2013) also concluded, from the morphology of a sample of H I-rich spiral galaxies, that the extended gas disks are not the result of merger activity, but possibly of cold accretion.

The gas accretion rate has been estimated by Lemonias *et al.* (2011) using the volume density of XUV disks in the local Universe, assuming that the far-UV emission from star formation is an indicator of recent gas accretion. They concluded that accretion can only account for about 23% of the local star formation rate.

More recently, Wang *et al.* (2014) traced the outer radial gas profiles for a sample of H I-rich galaxies, finding good agreement with the universal normalized profile measured for the THINGS galaxies by Bigiel & Blitz (2012). Their control sample deviates from this universal radial profile, showing less extended gas distributions perhaps due to low gas accretion rates or to evolutionary effects. The semi-analytical model presented by Wang *et al.*(2014) suggests that this universal H I profile is determined by the presence of recent gas accretion (again supporting the inside-out growth scenario), with an exponential distribution of the infalling gas.

The study of the kinematics of ten THINGS spiral galaxies by Schmidt *et al.* (2016) has revealed the presence of radial gas inflows, predominantly occurring in their outer disks. The mass flux is on the order of up to a few $M_\odot$ yr^{-1}, larger than the value of the SFR measured in the inner disks. While several factors are likely to be involved in regulating the star formation in the disks, including galactic winds and flow evolution, this finding seems to provide direct observational evidence for the large gas inflow rates that are required to sustain for several Gyrs the star formation activity in the inner disks, that are characterized by relatively short gas depletion timescales (few Gyrs).

4. Chemical abundances

In this section I briefly review observations of the gas-phase oxygen abundances ('metallicities') in the outer disks of spirals, as derived from optical spectroscopy of H II regions.

Spectra of a few H II regions located beyond the isophotal radii of the parent galaxies were obtained by Ferguson *et al.* (1998b) in NGC 628, NGC 1058 and NGC 6946, and, after the discovery of XUV disks with GALEX, by Gil de Paz *et al.* (2007) in M83 and NGC 4625. The main difficulty in measuring the O/H ratios in the outer disks is represented by the intrinsic faintness of the H II regions, which are typically ionized by a single hot star. In addition, given the systematic uncertainties in deriving nebular abundances and the double-valued nature of some of the nebular diagnostics, it is important to try and obtain emission-line information covering a wide spectral range, and possibly measure the gas electron temperature directly from auroral lines such as [O III]λ4363.

The two studies mentioned above were somewhat limited by the small number of objects observed at large galactocentric distances. The first investigation to obtain robust chemical abundances for a significant number of H II regions in the outer disk of a single galaxy was carried out by Bresolin *et al.* (2009), who obtained deep spectra of four different fields in the outer disk of M83 with the Very Large Telescope. The main chemical abundance characteristics of outer spiral disks, later confirmed by other investigations, are all showcased here: the flat radial gradient beyond R_{25}, contrasting the exponential decline in the inner disk, and the relatively high O/H value, at variance with the expectation that outer disks represent somewhat pristine regions of galaxies, with little signs of chemical evolution in their gas. These results were robust in the sense that they were obtained using different nebular abundance diagnostics, including N-based (eg. N2, O3N2) and O-based (eg. R23) line ratios. A few auroral line detections were also made, allowing to tie the strong-line indices results to the direct method.

Subsequent studies by the same group (Goddard *et al.* 2011, Bresolin *et al.* 2012) and others confirmed this general picture. For example, Werk *et al.* (2011) obtained flat abundance distributions in a sample of a dozen, mostly interacting galaxies. The stellar abundances show a similar behavior. Vlajic *et al.* (2009) used the colors of red giant branch stars as a proxy for their metallicity, and obtained a flat or even an inverted metallicity gradient in the outskirts of the Sculptor Group galaxy NGC 300. Kudritzki *et al.* (2014) confirmed the flattened abundance gradient in the outer disk of NGC 3621 obtained from H II regions by Bresolin *et al.* (2012), using blue supergiants as tracers of metals.

More recent results come from larger (but not as deep as some of the work mentioned above) spectroscopic surveys. Sánchez-Menguiano *et al.* (2016) presented results from the CALIFA project on 122 face-on spiral galaxies. They confirmed earlier results from the same survey (eg. Sánchez *et al.* 2012, 2014) that a flattening of the gas-phase oxygen abundance around a galactocentric distance corresponding to twice the effective radius is a common occurrence, with no apparent dependence on galactic mass, luminosity, and morphological type.

On the other hand, Moran *et al.* (2012) observed a downturn in O/H taking place beyond R_{90} for about 10% of their sample of 174 spirals from the GASS H I survey. They noted that the size of this drop increases with the H I gas fraction, a fact that they tentatively associate with gas accretion. Carton *et al.* (2015) also observed a similar downturn for a sample of 50 Bluedisk galaxies, but they do not find any correlation with the H I properties.

Flat oxygen abundance distributions can be observed out to galactocentric distances of several tens of kpc in the case of interacting systems. For example, Olave-Rojas *et al.*(2015) measured H II region abundances out to almost 70 kpc from the center of

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the galaxy NGC 6845, with a remarkably flat gradient. Flat abundance distributions are routinely observed in interacting systems (eg. Torres-Flores *et al.* 2014 for NGC 92), and are attributed to gas flows that result from the interaction mechanism itself (eg. Torrey *et al.* 2012, Rupke *et al.* 2010).

An interesting interacting system is represented by NGC 1512, which is experiencing an encounter with the companion NGC 1510. The flat and relatively high O/H abundance values in the outer disk have been studied by Bresolin *et al.* (2012) and, more recently, by López-Sánchez *et al.* (2015). These authors point out the effect of the interaction on the outlying northern spiral arm, where the O/H values have a much larger dispersion than in the opposite side of the galaxy.

4.1. *Clues on the evolutionary status of outer disks*

To summarize, the O/H abundances in the outer disks of spiral galaxies (i) display a flat radial distribution; (ii) are quite metal rich, given their large gas fraction and very low star formation rates, as pointed out by Bresolin *et al.* (2009, 2012) and Werk *et al.* (2010ab, 2011); finally (iii) there is a hint that in some systems there might be a discontinuity at the interface between the inner and outer disks.

There is a variety of explanations possible for the observed chemical properties of outer disks. First of all, interactions are known to be able to explain the flat radial distributions, but not all the outer-disk galaxies that have been studied are interacting or show signs of merging activity. A simple observation by Bresolin *et al.* (2012) suggested that the flat O/H distribution might be a consequence of the relatively flat star formation efficiency observed in outer disks (Bigiel *et al.* 2010, Espada *et al.* 2011), since the O/H ratio is proportional to the oxygen yield y_O multiplied by the ratio of the star formation surface density and the H I surface density, which, by definition, represents the star formation efficiency.

The mechanisms invoked by various authors to explain the flat and relatively high O/H values in outer disks can be broadly divided into two classes: radial mixing (see Bresolin *et al.* 2009, Werk *et al.* 2011) and enriched infall (see Bresolin *et al.* 2012). The former include those mechanisms that can bring metals generated in the inner disks directly into the outer disks, for example due to the action of bars, tidal interactions and satellite encounter, or due to radial gas flows (Lacey & Fall 1985) and viscous flows (Ferguson & Clarke 2001), resonance scattering with transient spiral density waves (Sellwood & Binney 2002) or spiral pattern/bar overlap (Minchev & Famey 2010). In the enriched infall scenario, the metals populate the outer disks via gas accretion modulated by feedback, outflows and star formation occurring in the inner disks, that enrich the circumgalactic medium via galactic winds (eg. Oppenheimer & Davé 2008) or SNe ejecta (Fu *et al.* 2013).

Minor merger activity has also been proposed to be effective at enriching the outer disks with metals (López-Sánchez *et al.* 2015, Lehnert *et al.* 2016). A further possibility, that would also help explain the presence of possible steps in the radial abundance distribution, is represented by corotation resonances (Scarano & Lépine 2013).

4.2. *Analogy with low surface brightness galaxies?*

It has been pointed out before that the structural parameters of outer spiral disks resemble those of low surface brightness (LSB) galaxies (eg. Thilker *et al.* 2007, Bresolin *et al.* 2009). Does the analogy extend to the chemical properties? That is, does a low star formation efficiency lead to a flat abundance distribution also in the case of LSB galaxies? The question remained without a clear answer until recently, because very few studies addressed the gas-phase chemical abundance properties of this type of galaxies, and in particular their abundance gradients. Bresolin & Kennicutt (2015) obtained H II region abundances for a sample of 10 LSB galaxies, with sufficient statistics to enable the investigation of the presence of abundance gradients. Indeed, they found that LSB galaxies do display radial abundance gradients which, when normalized by the effective radii, are consistent with those measured for high surface brightness galaxies. Thus, the analogy between LSB galaxies and the outer disks of spiral galaxies does not seem to extend to the chemical abundance properties.

4.3. *Links with surface brightness breaks*

Recently Marino *et al.* (2016) looked at the possible connections between outer disk abundance gradients and surface brightness breaks, discussed elsewhere in this volume, that characterize the disks of spiral galaxies. They focused on a subsample of 131 CALIFA galaxies displaying either Type II ('down-bending') or Type III ('up-bending') surface brightness profiles. Some correlation was found in the case of Type III galaxies. At smaller masses a small color flattening tends to be common, with only a mild flattening of the O/H gradient, while at higher masses both colors and O/H profiles display a marked flattening. The difference is tentatively attributed to the recent/current inside-out growth in the former case, while in the latter the inside-out growth could be less recent.

Future investigations of the chemical abundance properties of the outer disks of spiral galaxies will likely focus on the correlations with the gas content, shedding light on the interplay between chemical and secular evolution of the outer disks and accretion events.

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