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Metallicity gradients in nearby galaxies

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Abstract. I present an overview of recent observational developments in the study of extragalactic metallicity gradients in disk galaxies.

Key words. Galaxies: abundances

1. Introduction

The observational study of extragalactic chemical abundance gradients has a long history: the paper *'Evidence for composition gradients across the disks of spiral galaxies'* was published by L. Searle more than four decades ago (Searle 1971). Despite its maturity, the field has renewed its popularity in the last few years, thanks to a number of recent observational developments, which will be the focus of this brief review. From the theoretical viewpoint, exponential metallicity gradients originate in disk galaxies from the radial dependence of the rates of star formation and gas accretion. Chemical evolution models and simulations generally predict a flattening of these gradients as galaxies evolve, as a result of the inside-out formation of the disks (eg. Prantzos & Boissier 2000; Pilkington et al. 2012; but see Chiappini et al. 2001).

2. Gradients from massive stars

While the majority of present-day abundance gradients in star-forming galaxies relies on the analysis of the emission-line spectra of H II regions, it is essential to be able to provide independent measurements, for example to try and resolve the very large systematic uncertainties affecting the strong-line nebular diagnostics used ubiquitously in the literature (Kennicutt et al. 2003; Kewley & Ellison 2008). The use of low-resolution ($R = 1000$) spectrographs at 8m-class telescopes and state-of-the-art stellar model grids for massive stars (Kudritzki et al. 2008) allows us to measure metallicities of individual young, blue supergiants stars in galaxies out to several Mpc. Bresolin et al. (2009a) compared the abundance gradient for nearly 30 H II regions and a similar number of B- and A-type supergiants in the Sculptor Group galaxy NGC 300 ($D = 2$ Mpc), obtaining an impressive agreement not only for the slope of the gradient across the full galactic disk, but also for the absolute value of the abundances, when nebular abundances are obtained from the 'weak-line' method involving the [O III] λ4363 auroral line. However, more recent work in M81 (Kudritzki et al. 2012; Patterson et al. 2012) and M31 (Zurita & Bresolin 2012) suggests the emergence of discrepancies between nebular abundances based on the auroral-line method and stellar metallicities above the solar value.

3. Mergers

Hydrodynamical simulations of merging galaxies show how inflows can force metal-poor gas from the galaxy outskirts into their central regions, lowering the nuclear metallicities and flattening the abundance gradients (Rupke et al. 2010a). Observations show that interacting galaxies display flatter gradients (-0.017 ± 0.002 dex kpc^{-1}) than isolated ones (-0.041 ± 0.009 dex kpc^{-1}, Rupke et al. 2010b), and that flatter gradients are found for more advanced merger stages (Rich et al. 2012).

4. High-redshift galaxies

There is much interest in deriving abundance gradients in high-redshift disk galaxies, since this yields a direct test of the evolution of abundance gradients. Jones et al. (2010) and Yuan et al. (2011) reported the first determinations of the nebular abundance gradients in lensed galaxies at $z = 2$ and $z = 1.5$, respectively, obtaining much steeper slopes (-0.27 and -0.16 dex kpc^{-1}) than observed in the local universe. On the other hand, other studies of non-lensed systems (e.g. Cresci et al. 2010; Queyrel et al. 2012) found evidence for much flatter or even 'inverted' gradients in $z = 1.2$-3 galaxies, and proposing infall of metal-poor primordial gas or merger activity as an explanation. Future studies will need to establish whether these apparently contradictory results may be affected by spatial resolution or metallicity diagnostic issues.

5. Extended disks

Recent observational and theoretical breakthroughs in the study of spiral galaxies have shown that their outskirts play a major role in the understanding of galaxy assembly and evolution. It has been known for a long time (Freeman 1970) that the light distribution of spirals follows an exponential decline from the center to the outer edge of the disk (which essentially coincides with the isophotal radius R_{25}). The metallicity, as measured mainly from the oxygen abundance of H II regions, also displays an exponential falloff (see Henry & Worthey 1999 for a review). These properties are believed to represent signatures of the mechanisms by which galactic disks are assembled, as currently understood within the hierarchical galaxy formation framework, in which the observed radial dependencies are introduced by an inside-out growth of the galactic disks (e.g. Matteucci & Francois 1989; Naab & Ostriker 2006).

Evidence for weak star-formation activity in outer disks was provided by the discovery of galaxies with faint H II regions located well beyond R_{25} (Ferguson et al. 1998). The exponential decline of the surface brightness only rarely continues undisturbed to large radii (e.g. Pohlen & Trujillo 2006; Bakos et al. 2008). In 60% of the cases, a steeper profile is observed beyond R_{25}, but the broken profile can also be shallower at $R > R_{25}$, pointing to the presence of extended stellar disks. The direct detection of both young B-type and evolved stars (red giants and AGB stars) from resolved star counts at large galactocentric distances ($\sim 2 \times R_{25}$) has been reported in a few nearby spirals (Bland-Hawthorn et al. 2005; Vlajić et al. 2009; Davidge 2007, 2010).

Among the most significant recent developments in the characterization of outer galactic disks is the GALEX discovery that up to ~30% of star-forming galaxies in the local universe harbor significant levels of recent star formation, as seen in the form of young star clusters (Dong et al. 2008) distributed well beyond their optical edges (Gil de Paz et al. 2005; Thilker et al. 2007; Lemonias et al. 2011). This discovery has prompted several recent studies (Boissier et al. 2007; Goddard et al. 2010; Alberts et al. 2011) of the processes that convert gas into stars in a previously unexplored galactic environment, characterized by low gas densities, long dynamical timescales, and presumably low levels of chemical enrichment compared to the inner disks. Far-UV observations have shown that a significant fraction (up to 40%) of *early-type* galaxies, generally considered quiescent in terms of star formation, also contain young star clusters in their outskirts (Salim et al. 2012; Moffett et al. 2012).

The investigation of the chemical abundances of outer disks is of primary importance to understand whether these truly represent young, unevolved portions of spiral galaxies, and whether secular processes can affect the radial distribution of metals in the external regions of galaxies. While negative radial abundance gradients are well-established for inner spiral disks (Vila-Costas & Edmunds 1992; Zaritsky et al. 1994), and are crucial to interpret galactic chemical evolution, the study of the metal content of the outer regions of galaxies is still in its infancy, and solid theoretical predictions for its evolution are currently lacking. Bigiel et al. (2010) showed that the gas depletion times are extremely long ($\sim 10^{11}$ yr) in outer disks, compared to a few Gyr for the inner disks. Because of the very small efficiency in converting gas into stars, one would expect a very slow buildup of metals. However, the few available measurements of the present-day oxygen abundances in extended disks suggest otherwise.

In order to characterize the process of star formation in extended UV (XUV) disks, the author and his collaborators have worked in recent years to measure oxygen abundances (O/H, 'metallicities') of extremely faint H II regions located in the outskirts of nearby late-type, spiral galaxies: M83 (Bresolin et al. 2009b), NGC 4625 (Goddard et al. 2011), NGC 1512 and NGC 3621 (Bresolin et al. 2012). We obtained radial metallicity distributions that flatten to a virtually constant value beyond the optical, isophotal radius. Fig. 1 shows a schematic view of these results. In order to explain these findings, one can invoke various processes, which can be broadly divided into two classes: radial mixing and enriched infall. The relatively high O/H values we measure ($\sim$1/3 solar) in the outer disks lend support to the concept that gas accretion from the intergalactic medium, chemically enriched by galactic outflows ('wind recycling', Davé et al. 2011), is responsible for the rejuvenated star formation activity of XUV disks in spirals.

Other authors have recently worked on this subject. In the case of the dwarf galaxy NGC 2915 Werk et al. (2010) found a metal-enriched outer disk from an analysis of a few H II regions. Similar results have been found by Werk et al. (2011) for a sample of 13, mostly merging or interacting, galaxies. A flattening, possibly an upturn, in the metallicity gradient has also been detected from stellar photometry of the old, resolved stellar population (red giant branch stars) in the outer disks of NGC 300 (Vlajić et al. 2009). Evidence for a flat outer abundance gradient has also been found from a variety of stellar studies in the Milky Way (Pedicelli et al. 2009; Lépine et al. 2011).

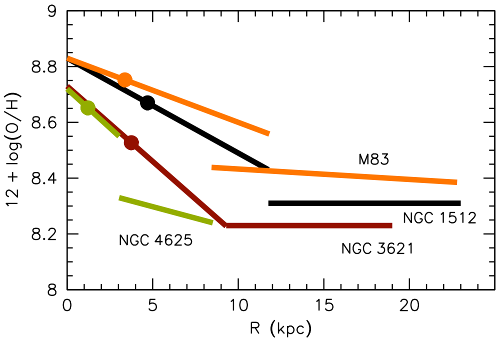

Fig. 1. Schematic representation of the galactocentric O/H abundance gradients obtained by our group for the extended disk galaxies M83, NGC 4625, NGC 1512 and NGC 3621. Dots are shown at $R = 0.4\,R_{25}$ for each galaxy to represent the characteristic abundances of their inner disks. (From Bresolin et al. 2012)

6. Low surface brightness galaxies

With their low levels of star formation and low surface gas densities, outer disks resemble low surface brightness galaxies (LSBGs). The star forming activity in LSBGs takes place at low, possibly subcritical, gas densities (de Blok et al. 1996), similar to the situation encountered in outer disks. The analogy can be extended even further: star formation in LSBGs appears to occur sporadically or intermittently, at extremely low rates (Gerritsen & de Blok 1999; van den Hoek et al. 2000; Boissier et al. 2008). At the low surface gas densities ($\Sigma_{HI} <$ $10\ M_\odot\,\mathrm{pc}^{-2}$) encountered in LSBGs and outer disks the star formation efficiencies are 5-10 times smaller than in high surface brightness galaxies (HSBGs), as shown by Boissier et al. (2003) and Wyder et al. (2009).

A handful of chemical abundance studies have so far been carried out for LSBGs. Virtually all of them have been limited to single-slit H II region spectroscopy from 4m-class telescope observations. The application of strong-line diagnostics yielded moderately low oxygen abundances, generally $12 + \log(O/H) < 8.2$ ($< 1/3$ solar; McGaugh 1994; Burkholder et al. 2001). This suggests that these are fairly unevolved systems, and the notion of 'slowly evolving' systems (McGaugh & de Blok 1997) might then fit the description of both extended disks *and* LSBGs.

The work by de Blok & van der Hulst (1998) suggested that there is no evidence for the presence of O/H gradients in LSBGs. This finding would be consistent with the sporadic star formation histories that are deduced for LSBGs. Therefore, both LSBGs and extended disks could favor a chemical evolution mode in which radial gradients do not develop. However, de Blok & van der Hulst (1998) reached their conclusion based on 3 LSBGs, in which only 4 to 7 H II regions have been studied spectroscopically. This important issue has yet to be readdressed with deeper and statistically more significant data.

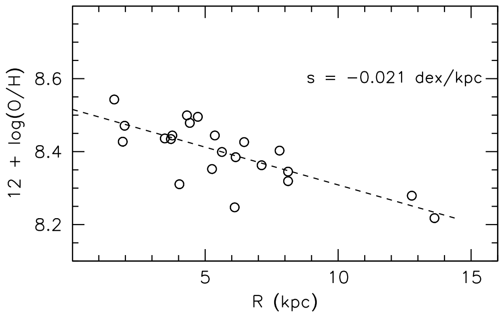

Fig. 2. Preliminary radial O/H abundance gradient of the LSBG ESO LV440-49 (VLT data).

In the past two years the author has carried out an observational program to probe the chemical composition of H II regions in 15 LSBGs with 8m-class telescope observations. The *preliminary* results contradict the de Blok & van der Hulst (1998) claim that LSBGs do not display radial abundance gradients. As Fig. 2 shows, significant abundance gradients can be found also in LSBGs. Whether this holds for the remaining galaxies in the observed sample, whether LSBGs have on average shallower gradient slopes than high surface brightness galaxies, and establishing what these observations imply for the possible analogy with outer disks, requires a full analysis of the newly acquired multi-object spectroscopy.

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