Chapter 5
Metallicities in the Outer Regions of Spiral Galaxies

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Abstract The analysis of the chemical composition of galaxies provides fundamental insights into their evolution. This holds true also in the case of the outer regions of spiral galaxies. This chapter presents the observational data, accumulated in the past few years mostly from the analysis of H II region spectra, concerning the metallicity of the outer disks of spirals that are characterized by extended H I envelopes and low-star formation rates. I present evidence from the literature that the metal radial distribution flattens at large galactocentric distances, with levels of enrichment that exceed those expected given the large gas mass fractions and the weak star formation activity. The interpretation of these results leads to speculations regarding mechanisms of metal mixing in galactic disks and the possibility that metal-enriched gas infall plays a role in determining the chemical evolution of the outskirts of spirals.

5.1 Introduction

The analysis of the chemical abundance composition of galaxies provides essential and unique constraints on their evolutionary status and their star formation properties. Gathering spatially resolved information about the distribution of metals is a well-tested approach to probe not only the metal production in stars across time but also those effects, such as galactic wind outflows, gravitational interactions, secular processes and gas inflows, that can profoundly affect the evolution of galaxies.

This chapter looks at the present-day gas metallicities of outer spiral disks, as derived from the emission-line analysis of H II region spectra, excluding older chemical abundance tracers, such as planetary nebulae and stars, except for a few notable exceptions. The connections between the chemical abundances of the outer disks thus derived and of the circumgalactic medium, probed by resonance absorption lines in the UV, for example, in damped Lyman α systems, are covered elsewhere in this volume (see the review by Chen 2017).

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A non-secondary aspect of chemical abundance work in nearby and faraway star-forming galaxies concerns the methodology employed in the measurement of nebular (ionized gas) abundances. Therefore, Sect. 5.2 provides a brief overview of the difficulties and the techniques used. The subsequent sections provide details on the work carried out in a variety of nearby systems (Sects. 5.3 and 5.4), building the framework for interpreting the observed chemical abundance properties (Sect. 5.5). A concise summary concludes the chapter.

5.2 Measuring Nebular Abundances

The measurement of nebular chemical abundances that are free of significant systematic uncertainties remains an unsolved problem in astrophysics, despite decades of observational efforts to investigate the emission-line properties of Galactic and extragalactic H II regions. Many authors (among others, Bresolin et al. 2004; Kewley and Ellison 2008; López-Sánchez et al. 2012) have addressed this issue, showing how the various emission-line diagnostics and the different calibrations proposed in the literature for these diagnostics are afflicted by systematic variations on the derived oxygen abundances that reach up to 0.7 dex.[1] This problem, of course, affects not only the investigation of ionized nebulae in the local Universe, e.g. for the analysis of abundance gradients in spiral galaxies (Vila-Costas and Edmunds 1992; Zaritsky et al. 1994; Kennicutt et al. 2003; Sánchez et al. 2014; Ho et al. 2015; Bresolin and Kennicutt 2015), but also the myriad of studies concerning the chemical composition of star-forming galaxies, notably those at high redshifts (e.g. to investigate the mass-metallicity relation), that rely on the local calibrations and the cosmic evolution of metals (Tremonti et al. 2004; Erb et al. 2006; Maiolino et al. 2008; Mannucci et al. 2010; Zahid et al. 2013; Sanders et al. 2015, to cite only a few).

In order to derive reliable chemical abundances of ionized nebulae, it is necessary to have a good knowledge of the physical conditions of the gas, in particular of the electron temperature T_e, because of the strong temperature sensitivity of the line emissivities of the various ions. An excellent source on the subject of deriving oxygen abundances in ionized nebulae is the monograph published by Stasińska et al. (2012). Nebular electron temperatures can be obtained through the classical, so-called *direct* method (Menzel et al. 1941), utilizing emission lines of the same ions that originate from different excitation levels and in particular from the ratio of the (collisionally excited) auroral [O III] λ4363 and nebular [O III] $\lambda\lambda$4959, 5007 lines. In the case of high-excitation (low-metallicity) extragalactic H II regions

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[1] In the literature measuring the *metallicity* of an H II region is equivalent to measuring its *oxygen abundance* O/H, since O constitutes (by number) approximately half of the metals. The standard practice is to report the value of $12 + \log(\mathrm{O/H})$. The Solar value used for reference is taken here to be $12 + \log(\mathrm{O/H})_\odot = 8.69$, from Asplund et al. (2009).

and planetary nebulae, the [O III] λ4363 line is often detected, but it becomes unobservable as the cooling of the gas becomes efficient at high metallicity or whenever the objects are faint, so that properly calibrated *strong-line* abundance diagnostics become necessary in order to infer the oxygen abundances. However, even for nebulae where [O III] λ4363 can be observed, a poorly understood discrepancy exists between the nebular abundances based on the direct method and those obtained from emission-line strengths calibrated via photoionization model grids (McGaugh 1991; Blanc et al. 2015; Vale Asari et al. 2016). A 0.2–0.3 dex discrepancy (T_e-based abundances being lower) is also found when using the weak metal *recombination* lines, in particular the O II lines around 4650 Å, instead of the collisionally excited lines (García-Rojas and Esteban 2007; Esteban et al. 2009; Toribio San Cipriano et al. 2016). On the other hand, comparisons of stellar (B and A supergiants) and nebular chemical compositions in a handful of galaxies (see Bresolin et al. 2009a) provide a generally good agreement when the nebular abundances are calculated from the direct method, at least for subsolar metallicities.

Despite the somewhat unsatisfactory situation illustrated above, we can still derive robust results concerning the metallicities of outer disk H II regions. As will become apparent later on, it is important to highlight two results. Firstly, radial abundance trends in spiral disks are generally found to be qualitatively invariant relative to the selection of nebular abundance diagnostics, although different methods can yield different gradient slopes (see Bresolin et al. 2009a; Arellano-Córdova et al. 2016). Secondly, O/H values that are derived from direct measurements of T_e or from strong-line diagnostics that are calibrated based on [O III] λ 4363 detections lie at the bottom of the possible abundance range, when compared to metallicities derived from other diagnostics, such as those based on theoretical models.

The literature on nebular abundance diagnostics is vast (a recent discussion can be found in Brown et al. 2016), and for the purposes of this review, it is important only to recall a few of the most popular ones and (some of) their respective calibrations:

1. O3N2 $\equiv \log[([\mathrm{O\,III}]\,\lambda 5007/\mathrm{H}\beta)/([\mathrm{N\,II}]\,\lambda 6583/\mathrm{H}\alpha)]$, calibrated empirically (i.e. based on T_e detections in H II regions of nearby galaxies) as given by Pettini and Pagel (2004) and, more recently, by Marino et al. (2013).
2. N2O2 $\equiv [\mathrm{N\,II}]\,\lambda\ 6583/[\mathrm{O\,II}]\,\lambda 3727$, calibrated from photoionization models by Kewley and Dopita (2002) and empirically by Bresolin (2007). Bresolin et al. (2009b) showed that these two calibrations yield abundance gradients in spiral disks that have virtually the same slopes, despite a large systematic offset.
3. N2 $\equiv [\mathrm{N\,II}]\,\lambda 6583/\mathrm{H}\alpha$, calibrated by Pettini and Pagel (2004) and Marino et al. (2013).
4. R23 $\equiv ([\mathrm{O\,II}]\,\lambda 3727 + [\mathrm{O\,III}]\,\lambda\lambda 4959, 5007)/\mathrm{H}\beta$ (Pagel et al. 1979). Many different calibrations have been proposed through the years (e.g. McGaugh 1991; Kobulnicky and Kewley 2004). This diagnostic can be important in order to verify whether the metallicity gradients derived from other strong-line techniques, mostly involving the nitrogen [N II] λ6583 line, are corroborated by

considering only oxygen lines instead. Unfortunately, the use of this indicator for abundance gradient studies is complicated by the non-monotonic behaviour of R23 with oxygen abundance. The simultaneous use of a variety of diagnostics, when the relevant emission lines are available, alleviates this problem. The empirically calibrated P-method (Pilyugin and Thuan 2005) and some related diagnostics (e.g. Pilyugin and Grebel 2016) also make use of both the [O II] and [O III] strong emission lines.

To summarize, a variety of optical emission-line diagnostics are available to derive the metallicities (oxygen abundances) of extragalactic H II regions. Due to poorly known aspects of nebular physics (e.g. temperature fluctuations), absolute metallicities remain a matter of debate, especially at high (near-Solar) values. On the other hand, relative abundances within galaxy disks are quite robust. T_e-based oxygen abundances lie at the bottom of the distribution of values obtained from the set of metallicity diagnostics currently available.

5.3 Chemical Abundances of H II Regions in Outer Disks

While the spectroscopic analysis of H II regions in the inner disks of spiral galaxies is a well-developed activity in extragalactic astronomical research, starting with the pioneering work by Searle (1971) and Shields (1974), who provided the first evidence for the presence of exponential radial abundance gradients in nearby galaxies such as M33 and M101, the investigation of ionized nebulae located beyond the boundary of the main star-forming disk has begun only recently. Observationally, the main difficulty in measuring chemical abundances in these outlying H II regions is represented by their intrinsic faintness. In fact, these nebulae are typically ionized by single hot stars, as deduced from their Hα luminosities (Gil de Paz et al. 2005; Goddard et al. 2010), that are on average about two orders of magnitude fainter than those of the giant H II regions that are routinely observed in the inner disks (Bresolin et al. 2009b; Goddard et al. 2011). This section reviews the investigations of the chemical abundances in the outskirts of nearby spiral galaxies, focussing mostly on oxygen in H II regions. Studies of metals in old stars and nebular nitrogen are also briefly discussed.

5.3.1 Early Work

Spectra of a handful of outlying H II regions in the disks of the late-type spirals NGC 628, NGC 1058 and NGC 6946, known for their extended H I distributions, were first obtained by Ferguson et al. (1998). These authors found that the oxygen abundance gradients measured in the inner disks appear to continue to large galactocentric distances, beyond the isophotal radii[2] R_{25}, and reaching low metallicities, corresponding to 10–15% of the Solar value. Unfortunately, the small sample size concealed the possibility, demonstrated by later work, that the radial metallicity trends could actually be different between inner and outer disks. van Zee et al. (1998) also presented spectra of outlying H II regions in a sample of 13 spirals, but the number of objects observed near R_{25} and beyond was very small.

The oxygen abundance in the outer disks of two iconic representatives of the class of extended UV (XUV) disk galaxies discovered by the *GALEX* satellite, M83 (Thilker et al. 2005) and NGC 4625 (Gil de Paz et al. 2005), was investigated by means of multi-object spectroscopy with the Magellan and Palomar 200-in. telescopes by Gil de Paz et al. (2007). These authors also found a relatively low metal content, around 10–20% of the Solar value, utilizing a combination of photoionization models and the R23 strong-line abundance diagnostic. This study, however, was also limited by the small number of H II regions observed at large galactocentric distances, especially for the galaxy NGC 4625. A feature of the M83 radial abundance gradient that was suggested by Gil de Paz et al. (2007), i.e. a sudden drop in metallicity at a galactocentric distance of 10 kpc, but whose presence was dubious due to the uncertain O/H ratios derived from R23, was also detected later in the larger sample of outlying H II regions studied by Bresolin et al. (2009b). Gil de Paz et al. (2007) remarked that such a sharp decrease, if present, could be the signature of a transition to an outer disk where the star formation efficiency is significantly lower compared to the inner disk.

5.3.2 M83: A Case Study

The first investigation to obtain robust chemical abundances—via a variety of nebular metallicity diagnostics—in the outer disk of a single galaxy was carried out by Bresolin et al. (2009b), who obtained spectra of ionized nebulae in the outer disk of M83 with the ESO Very Large Telescope. Of these H II regions, 32 lie at galactocentric distances larger than the isophotal radius, extending out to 22.3 kpc (2.64 R_{25}) from the galaxy centre.

The principal chemical abundance properties of the outer disks of spiral galaxies, confirmed by subsequent investigations of other targets (as discussed in the next pages), are all showcased in this prototypical XUV disk galaxy (see Fig. 5.1):

- The nearly flat radial gradient beyond R_{25}, contrasting with the steeper exponential decline observed in the inner disk. The gradient slope found for the inner disk

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[2] At the isophotal radius R_{25} the surface brightness measures 25 mag arcsec^{-2} and is often reported in the B photometric band, as in the Third Reference Catalogue of Bright Galaxies (de Vaucouleurs et al. 1991).

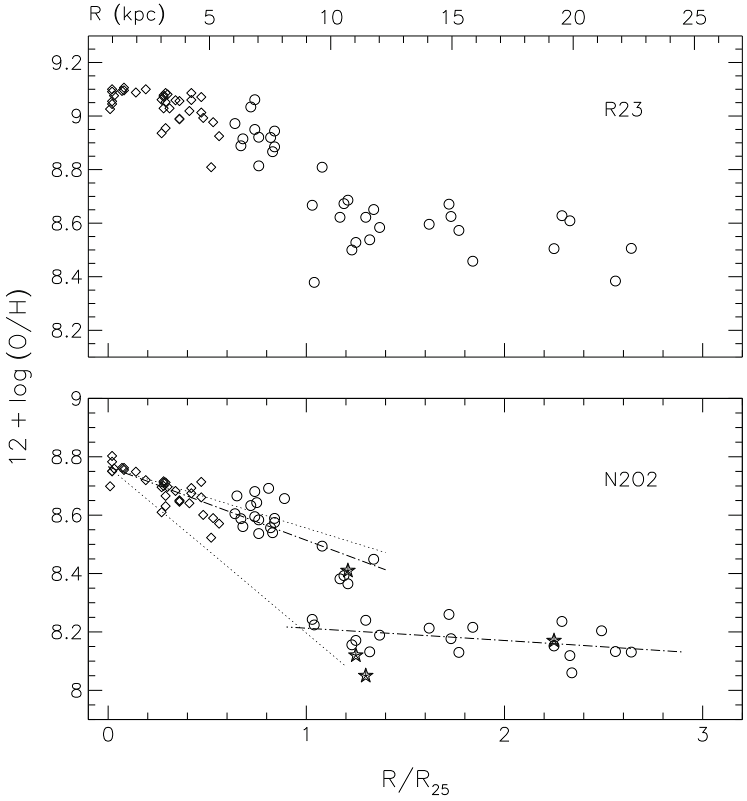

Fig. 5.1 The radial oxygen abundance gradient in M83, determined from two different diagnostics (R23 in the *top panel*, N2O2, as calibrated empirically by Bresolin (2007), in the *bottom panel*), from H II regions located in the inner disk (*open diamond*: Bresolin and Kennicutt 2002; Bresolin et al. 2005) and in the outer disk (*open circle*: Bresolin et al. 2009b). The *star symbol* represents [O III] λ4363-based O/H values. Linear regressions to the radial abundance gradient are shown as separate *dot-dashed lines* for the inner and outer portions of the galactic disks. The *two dotted lines* represent the range of gradient slopes measured by Ho et al. (2015) from a sample of 49 galaxies: $\mathrm{d}\log(\mathrm{O/H})/\mathrm{d}R = -0.39 \pm 0.18$ dex R_{25}^{-1}. Adapted from the data published by Bresolin et al. (2009b)

using the N2O2 diagnostic

$$\frac{\mathrm{d}\log(\mathrm{O/H})}{\mathrm{dR}} = -0.25 \pm 0.02\ \mathrm{dex}\, R_{25}^{-1} \tag{5.1}$$

compares well with the benchmark value of -0.39 ± 0.18 dex R_{25}^{-1} measured by Ho et al. (2015) from a sample of 49 galaxies (the two dotted lines in Fig. 5.1 show the two extreme values of the one-sigma range). On the other hand, in the outer disk, a linear fit to the data displayed in Fig. 5.1 yields a slope

$$\frac{\mathrm{d}\log(\mathrm{O/H})}{\mathrm{dR}} = -0.04 \pm 0.02\ \mathrm{dex}\, R_{25}^{-1}, \tag{5.2}$$

i.e. nearly flat. Clearly, the radial behaviour of the gas metallicity differs significantly between the inner, star-forming disk of M83, and the outer disk.

- The relatively high mean O/H value measured at large galactocentric distances. This value depends on the selection of abundance diagnostic, as explained in Sect. 5.2. In the work presented by Bresolin et al. (2009b), it lies in the range $12 + \log(\mathrm{O/H}) = 8.2$–$8.6$, i.e. between ~30% and ~80% of the Solar value, depending on whether the abundances are tied to T_e-based detections (lower value) or whether they are determined from photoionization models (upper value). It is worth pointing out that the few detections of the [O III] λ4363 auroral line lead to O/H ratios (star symbols in Fig. 5.1) that are quite consistent with those determined from the empirically calibrated N2O2 diagnostic.

  This result on the metallicity of the outer disk of M83 is at odds with the expectation that the very outskirts of spiral galaxies are somewhat pristine and chemically unevolved, as would be implied by a simple picture of inside-out galactic formation. I draw attention to the fact that adopting abundance diagnostics that are calibrated via photoionization models, the outer disk of M83 would have a mean metallicity that is nearly Solar. Using a more conservative approach, we can say that the mean metallicity of the outer disk is *at least* 1/3 Solar, based on the summary presented at the end of Sect. 5.2.

  Bresolin et al. (2009b) also pointed out that the extended disk of M83 should be considered chemically over-enriched given its large gas mass fraction (approaching unity) when compared to a closed-box chemical evolution model, the opposite behaviour of what is observed, for example, in dwarf galaxies (Matteucci and Chiosi 1983, see also the explanatory text for Eq. (5.3)). This point will be further discussed in Sect. 5.3.3.

Figure 5.1 also suggests the presence of a ~0.2 dex oxygen abundance discontinuity beyond the isophotal radius. This feature is not confirmed by all abundance diagnostics considered (see also Pilyugin et al. 2012), nor is it detected in other extended disk galaxies, except NGC 4625 (Goddard et al. 2011), but it also appears in the data presented by Gil de Paz et al. (2007). It resembles the break occurring for the α-elements measured for Cepheids in the Milky Way at a galactocentric distance of approximately 9 kpc (Lépine et al. 2014).

The observations in M83 demonstrate that spectroscopy of H II regions located in the extended, gas-rich disks of spiral galaxies allows us to probe the present-day chemical abundances of external galactic disks out to nearly three isophotal radii, equivalent—in the case of M83—to more than 20 kpc. The interesting, and somewhat surprising, result is found that the radial metallicity distribution becomes virtually flat in the extended outskirts, with a value of at least 1/3 of Solar. The extended disk appears to be chemically overabundant for its very large gas mass fraction.

5.3.3 Other Systems

In this section the results obtained from other investigations of single targets or small samples of galaxies, essentially confirming and expanding the general picture outlined in Sect. 5.3.2 for M83, are reviewed. In addition to H II regions as primary probes of the present-day metallicity, information from the older stellar content is included. Some galaxies display a flattening of the gas metallicity already inside the main disk ($R < R_{25}$), perhaps as a result of gas flows induced by the gravitational potential of a stellar bar (Martin and Roy 1995; Zahid and Bresolin 2011; Marino et al. 2012). Here, I will focus on outer disk systems exclusively.

H I-Selected Galaxies The oxygen abundances of outlying H II regions in a sample of 13 H I-selected galaxies were measured using the R23 method by Werk et al. (2011). The sample is dominated by interacting systems and galaxies displaying a disturbed, extended neutral gas morphology. In most cases a flat radial abundance distribution was found across most of the disk of these systems, although the number of H II regions observed per galaxy is sometimes too small to infer variations between the inner and outer disks. Thus, the flattening observed can be of a different nature in this kind of galaxies (see the discussion below) compared with relatively isolated galaxies such as M83, where the flattening is observed to occur only in the outer disk.

Werk et al. (2011) showed that the oxygen abundances in the outskirts of the galaxies included in their sample are considerably higher than expected, given their large gas content compared with the total baryonic (stars + gas) mass. The same result was described by Bresolin et al. (2009b) and Werk et al. (2010) for the extended disks of M83 and the blue compact dwarf galaxy NGC 2915, respectively. While for typical star-forming galaxies the effective oxygen yield, defined by

$$y_{\mathrm{O,eff}} = \frac{Z_{\mathrm{O}}}{\ln(\mu^{-1})}, \tag{5.3}$$

where μ is the gas mass fraction and Z_{O} is the metallicity equivalent to the O mass fraction,[3] lies below the theoretical oxygen yield for a stellar population, $y_{\mathrm{O}} \simeq 0.007$ (e.g. Kobayashi et al. 2006), in the case of the outer disks, the opposite holds, with $y_{\mathrm{O,eff}} > 0.02$ (Werk et al. 2011; López-Sánchez et al. 2015). This in essence implies that the oxygen abundances measured in the gas located in the outskirts

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[3] The gas mass fraction is $\mu = M_{\mathrm{gas}}/(M_{\mathrm{gas}} + M_{\mathrm{stars}})$. The O mass fraction ("metallicity") and the abundance by number are linked by the relation $Z_{\mathrm{O}} = 11.81$ (O/H). The coefficient of proportionality is calculated as $16X$, adopting the hydrogen mass fraction for Solar composition from Asplund et al. (2009).

of these galaxies, including the XUV disk systems, characterized by extended H I envelopes, exceed the values predicted by the closed-box galactic chemical evolution model. How this level of chemical enrichment can be attained, given the low values measured for the star formation rate, will be addressed in Sect. 5.5.

Interacting Systems The majority of the galaxies studied by Werk et al. (2011) are located in interacting systems. Nebular oxygen abundances have been measured in the main star-forming disks and along tidal features of interacting and merging systems by various authors (e.g. Rupke et al. 2010b; Rich et al. 2012; Torres-Flores et al. 2014), finding significantly flatter radial distributions compared to noninteracting systems. These studies are supported by numerical simulations (Rupke et al. 2010a; Torrey et al. 2012), showing that gas flows induced by galaxy interactions redistribute the gas in such a way that the original abundance gradients—present in the galactic disks before the merging process—flatten progressively with merger stage.

This redistribution and radial mixing of metals can take place over very large distances, in extreme cases reaching several tens of kpc. For example, Olave-Rojas et al. (2015) measured the chemical abundances of H II regions located along the main tidal tail of NGC 6845A, part of a compact, interacting group of galaxies, out to almost 70 kpc from the centre (approximately $4\,R_{25}$). The radial oxygen distribution displays a remarkably shallow gradient.

An interesting interacting system is represented by NGC 1512, which is experiencing an encounter with the companion galaxy NGC 1510. The system, an XUV disk galaxy, is embedded in a very extended H I envelope, with a radius of 55 kpc (Koribalski and López-Sánchez 2009), in which low-level star formation is taking place, as shown by the far-UV and Hα emission originating from low-luminosity stellar complexes and associated H II regions. The flat and relatively high O/H abundance values, $12 + \log(\mathrm{O/H}) \simeq 8.3$, out to a galactocentric distance of $\sim$30 kpc, have been studied by Bresolin et al. (2012) and, more recently, by López-Sánchez et al. (2015). The latter authors point out the effect of the interaction on the outlying northern H I spiral arm, where the O/H values have a much larger dispersion than in the opposite side of the galaxy, which remains relatively undisturbed by the ongoing interaction.

Old Stars The data discussed so far refer only to the present-day metallicities, as derived from H II region emission. It is also possible to infer the chemical composition of the outer disks of nearby spirals from stellar photometry of older populations, in particular of red giant branch (RGB) stars. The method requires the photometry of individual stars, and as such has successfully been applied only to nearby systems, out to approximately 3 Mpc. Care must be taken in interpreting these photometric metallicities when discussing disk radial gradients, because of the potential contamination from halo stars.

The metallicity can be derived from a comparison of the observed stellar colours, such as $V-I$, with theoretical stellar tracks, exploiting the fact that these broadband colours are more sensitive to metallicity than age. In this way, Worthey et al. (2005) obtained a flat metallicity gradient in the outer disk of M31, between 20 and

50 kpc from the galaxy centre (1–2.5 R_{25}), with a mean value of [Z/H] $\simeq -0.5$. The published H II region abundances (e.g. Zurita and Bresolin 2012; Sanders et al. 2012) do not extend beyond 25 kpc, and thus whether a similar behaviour is encountered for the younger stellar populations cannot be verified. A flat gradient, with an approximately Solar O/H value, extending out to $\sim$100 kpc, has been reported for planetary nebulae by Balick et al. (2013) and Corradi et al. (2015). These authors attribute this finding to a star formation burst following interactions and merger processes, perhaps related to an encounter with M33, that occurred approximately 3 Gyr ago.

Vlajić et al. (2009, 2011) measured the metallicity of RGB stars from deep g' and i' Gemini photometry in the outer disks of the two Sculptor Group spirals NGC 300 and NGC 7793, out to 15 kpc (2.3 R_{25}) and 11.5 kpc (2.4 R_{25}), respectively. Both galaxies, like M31, display purely exponential surface brightness profiles out to these large galactocentric distances, indicating that the halo contribution is probably negligible. The possible connection between gas-phase metallicity and surface brightness profiles will be briefly discussed in Sect. 5.4.1.

For both NGC 300 and NGC 7793, the stellar metallicity flattens out to an approximately constant value or even slightly increases with radius in the outer disk, in contrast with the exponential decline inferred from H II regions and young stars in the inner disk. The measured metallicity is quite low, [Fe/H] $\simeq -1$ for the outer disk of NGC 300 and [Fe/H] $\simeq -1.5$ (or even lower, depending on the age of the stars) for NGC 7793, but could be compatible with the present-day metallicity of the inner disk if the chemical enrichment due to stellar evolution between the time probed by the RGB stars (8–12 Gyr ago) and the present epoch is taken into account. These results are made somewhat uncertain by the age-metallicity degeneracy, the assumption of a single age for the RGB stars and the potential effects of stellar migration.

Other XUV Disks The chemical abundances of outer H II regions in a few XUV disk galaxies (as defined in the catalogue by Thilker et al. 2007), in addition to M83 and NGC 1512, have been presented by different authors. For convenience, Table 5.1 summarizes these studies. These investigations differ somewhat in spectroscopic depth, abundance diagnostics adopted and radial coverage, but they tend to provide

Table 5.1 Nebular abundance studies in XUV disks

Galaxy	References	Largest radius (R_{25} units)
NGC 628	Rosales-Ortega et al. (2011)[a]	1.7
NGC 1512	Bresolin et al. (2012)	2.2
	López-Sánchez et al. (2012)	2.8
NGC 3621	Bresolin et al. (2012)	2.0
NGC 4625	Goddard et al. (2011)	2.8
NGC 5253 (M83)	Bresolin et al. (2009a,b)	2.6

[a] Data for objects lying beyond R_{25} extracted from Ferguson et al. (1998)

a unified picture regarding the abundance gradients, in particular the presence of a break occurring approximately at the isophotal radius, as a dividing point between the inner disk, characterized by an exponential nebular abundance gradient, and the outer disk, with a shallower or flat abundance gradient.

Not included in Table 5.1 is NGC 3031 (M81), for which a flat outer gradient has been suggested, but this result relies on a very small sample of outlying H II regions (Patterson et al. 2012; Stanghellini et al. 2014). A more recent work by Arellano-Córdova et al. (2016) does not find evidence for a flat gradient out to a galactocentric distance of 33 kpc (2.3 R_{25}). This seems to be consistent with the shallow overall abundance gradient, both in dex kpc^{-1} and normalized to the isophotal radius, which is possibly the consequence of galaxy interactions. It is also worth pointing out that the abundance break observed in NGC 3621 by Bresolin et al. (2012) has been confirmed by the independent spectroscopic analysis of five blue supergiant stars, straddling the isophotal radius, by Kudritzki et al. (2014). The stellar metallicities are intermediate between the nebular metallicities determined from the N2 and R23 diagnostics. Finally, it is important to notice that the sample presented above includes fairly isolated systems (NGC 3621, M83, NGC 628), ruling out the possibility that abundance breaks and significant metal mixing develop only as a consequence of recent galaxy interactions.

The Milky Way Evidence for a flattening of the abundance gradient in the outer disk of the Milky Way comes from observations of various metal tracers, which also sample populations with different ages: Cepheid variables (Korotin et al. 2014), open clusters (Magrini et al. 2009; Yong et al. 2012) and H II regions (Vílchez and Esteban 1996; Esteban et al. 2013). This break appears at a galactocentric distance around 12 kpc, extending outwards to 19–21 kpc, as shown from either Cepheids (Genovali et al. 2015) or open clusters (Carraro et al. 2004). While the flattening in the Cepheid chemical abundances is still somewhat controversial (e.g. Lemasle et al. 2013), the open clusters show a clear bimodal radial gradient in metallicity (Yong et al. 2012), the outer gradient being quite shallow, with a characteristic outer disk metallicity [Fe/H] $\simeq -0.3 \pm 0.1$. Further studies of the behaviour of the radial distribution of the stellar metallicity (and chemical element patterns) in the outer disk of the Galaxy will be important to constrain models of the chemical evolution of the Milky Way and the effects of the corotation resonance and stellar radial migration (Mishurov et al. 2002; Lépine et al. 2011; Korotin et al. 2014).

5.3.4 Results from Galaxy Surveys

More recent results about the chemical abundances of the outer disks of spiral galaxies in the nearby Universe have been published as part of relatively large spectroscopic surveys, largely dedicated to the measurement of emission-line abundances of the interstellar medium in the parent galaxies. These surveys, based on 4 m-class telescope observations, do not reach emission-line levels as faint as those probed by some of the single galaxy work illustrated earlier. Therefore, weak lines such as [O III] λ 4363 remain undetected in the low-luminosity H II regions located in the galactic outskirts. In addition, these surveys have provided metallicity information out to $\sim$1–1.5 R_{25}, i.e. to considerably smaller galactocentric distances than possible with 8 m-class facilities (see Table 5.1). On the other hand, the large number of galaxies (hundreds) provides essential statistical information about the properties of the abundance gradients, which are necessary to establish, for instance, how common radial metal distribution breaks are within the general population of spiral galaxies. Furthermore, such surveys also enable the investigation of possible correlations between abundance gradients and galactic attributes, such as mass, star formation rate and structural properties (e.g. the presence or absence of bars).

Integral Field Spectroscopy Sánchez-Menguiano et al. (2016) presented oxygen abundance measurements obtained by the Calar Alto Legacy Integral Field Area (CALIFA) project (Sánchez et al. 2012) in 122 face-on spiral galaxies. Adopting the O3N2 nebular diagnostic, they confirmed earlier results, obtained from the same survey (Sánchez et al. 2014), that a flattening of the gas-phase oxygen abundance taking place around a galactocentric distance corresponding to twice their effective radii[4] (R_e, measured in the r band) is a common occurrence in spiral disks. About 82% of the sample with reliable abundance data in the outer disks show this effect, with no apparent dependence on galactic mass, luminosity and morphological type. The oxygen abundance in the inner disks, on the other hand, follows a gradient having a characteristic slope of approximately -0.07 dex R_e^{-1}, except for the very central parts (Sánchez et al. 2014). This common behaviour is illustrated in Fig. 5.2, which displays data extracted from Sánchez-Menguiano et al. (2016, their Fig. 9).

In order to make these results more easily comparable with those presented earlier, where the radial normalization is done relative to the isophotal radius, we need to define a relation between R_e and R_{25}, which depends on the central surface brightness value (μ_0) for the adopted exponential brightness profile. Taking $\mu_0 = 21.65$ mag arcsec^{-2} from Freeman (1970), and using $\mu(R) = \mu_0 + 1.086 R/R_d$, one obtains $R_{25} = 1.84\,R_e$. Thus, the flattening in the abundance gradient observed for the CALIFA sample of galaxies to occur at $R \sim 2\,R_e$ or, equivalently, around $R \sim R_{25}$ is consistent with what is reported in Sects. 5.3.2 and 5.3.3. The O3N2-based oxygen abundances measured in the outer disks, out to $\sim$1.5 R_{25}, are also roughly consistent with those presented earlier; in particular they represent a significant fraction of the Solar value, e.g. approximately 0.5 (O/H)$_\odot$ for the intermediate-mass bin shown in Fig. 5.2.

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[4] The effective radius R_e encloses 50% of the light, integrated by adopting an exponential radial profile of the surface brightness (i.e. not including the contribution from the bulge): $I = I_0 \exp[-(R/R_d)]$, with I_0 the central intensity and R_d the disk scale length. The effective radius is given by $R_e = 1.678\,R_d$ (e.g. Graham and Driver 2005).

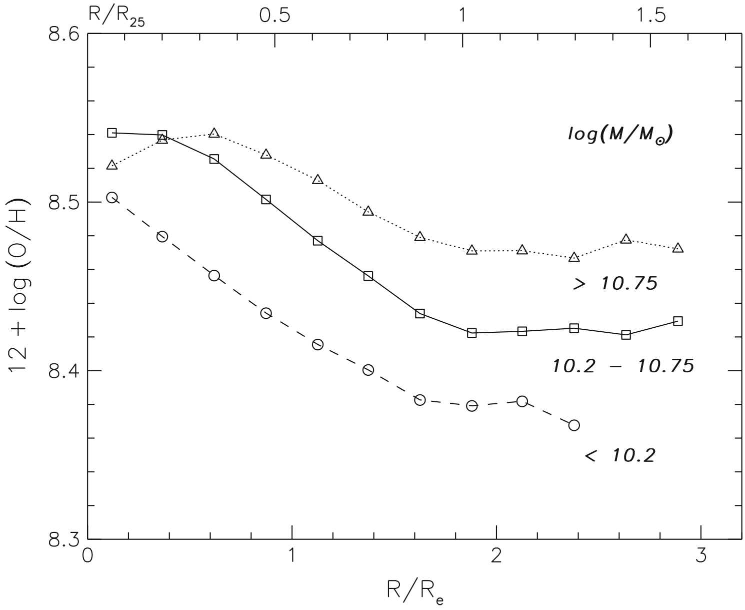

Fig. 5.2 Mean radial oxygen abundance profiles measured for a sample of face-on spirals from the CALIFA survey. The data are plotted in bins of 0.25 R_e, for three different galaxy mass ranges, as indicated in the plot. The upper scale, drawn in units of the isophotal radius, assumes a central surface brightness $\mu_0 = 21.65\,\mathrm{mag\,arcsec}^{-2}$. Adapted from Sánchez-Menguiano et al. (2016, Fig. 9)

Long-Slit Spectra For completeness, some additional surveys that obtained spectroscopic observations of the ionized gas in regions close to the edges of spiral galaxies are worth mentioning, even though the radial coverage is not as extended as in the cases discussed so far and is generally limited to regions inside the isophotal radius. Moran et al. (2012) obtained long-slit spectra along the major axis of 174 star-forming galaxies from the *GALEX* Arecibo Sloan Digital Sky Survey (Catinella et al. 2010) with stellar mass $M > 10^{10}\,M_\odot$ and determined O3N2-based gas-phase oxygen abundances in spatial bins for 151 galaxies displaying emission lines. However, their data extend to galactocentric distances of about $1.5\,R_{90}$[5] or approximately $0.9\,R_{25}$ according to the transformation between the two normalization radii estimated by these authors. Thus, these chemical abundances still refer to the main star-forming disk and should not be compared directly with the outer disk abundance properties presented in the previous sections. Interestingly, however, for about 10% of their galaxies, Moran et al. (2012) measured a significant drop in O/H around $R = R_{90}$, whose magnitude correlates with the total H I mass

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[5] R_{90} encloses 90% of the galaxy light, including the bulge.

fraction. These authors suggest that the downturn in oxygen abundance results from the accretion of relatively metal-poor gas in the outer regions of these galaxies.

Similar long-slit observations have been carried out by Carton et al. (2015) for 50 H I-rich galaxies, part of the Bluedisk survey (Wang et al. 2013), with a radial coverage extending to about $2\,R_{90}$ in some cases. Also for these targets, a steepening of the radial abundance distribution is observed at large radii. However, in this work the oxygen abundance downturn is not found to correlate with the H I properties of the parent galaxies as instead found in the work by Moran et al. (2012).

5.3.5 Nitrogen Abundances

The investigation of nitrogen abundances in extragalactic H II regions, and in particular of the N/O abundance ratio, provides important constraints on the chemical evolution of galaxies. This springs from the fact that, while oxygen is the nucleosynthetic product of massive stars ($M > 8M_{\odot}$), nitrogen, whose abundance can in general be easily measured in nebular spectra[6], originates mostly in intermediate-mass ($M = 1{-}8M_{\odot}$) stars (Henry and Worthey 1999). A look at the N/O ratio variation as a function of metallicity O/H in extragalactic nebulae reveals a bimodal behaviour. The N/O ratio is approximately constant [log(N/O) $\simeq -1.4$, but with a large scatter, see Garnett 1990] below $12 + \log(\mathrm{O/H}) = 8.0$ and increases with O/H at larger metallicities. This is interpreted in terms of a primary production of nitrogen, which is what is predominantly being measured at low metallicity, and of a secondary component, proportional to the oxygen abundance, dominating at high O/H (Vila Costas and Edmunds 1993). The N/O ratio measured in outer disk H II regions conforms to this trend, as shown by Bresolin et al. (2012). Since the oxygen abundances measured in outer spiral disks are generally below the level at which secondary nitrogen production becomes predominant, the radial trend of the N/O abundance ratio is virtually flat, with log(N/O) $\simeq -1.3$ to -1.5, in these outer regions (Bresolin et al. 2009b; Berg et al. 2012; López-Sánchez et al. 2015). A similar behaviour has recently been observed by Croxall et al. (2016) in M101 (also an XUV galaxy; Thilker et al. 2007), with the onset of the flattened N/O radial distribution occurring around $0.7\,R_{25}$. These results stress the fact that primary production of nitrogen dominates in the H II regions populating the outskirts of spiral galaxies.

In summary, flat abundance gradients and relatively high oxygen abundances appear to be common features of star-forming outer disks.

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[6] The N/O abundance ratio is obtained from the [N II] $\lambda\lambda$6548,6583/[O II] λ3727 line ratio, using the commonly adopted ionization correction scheme $\mathrm{N^+/O^+} = \mathrm{N/O}$.

5.4 Additional Considerations

To conclude the discussion of the observational constraints on the metallicity of the outer regions of spiral galaxies, I include two additional topics that have been addressed by recent work. Future investigations of the chemical abundance properties of the outer disks of spiral galaxies will benefit from the study of the spatially resolved gas content (both atomic and molecular), which will help to shed light on the interplay between chemical and secular evolution of the outer disks and accretion events or gas flows taking place in the very outskirts of galaxies.

5.4.1 Relation Between Metallicity and Surface Brightness Breaks

Recent work by Marino et al. (2016) probed into the possible connection between outer disk abundance gradients and surface brightness profile breaks that characterize the disks of spiral galaxies, as discussed elsewhere in this volume. These authors focussed on 131 galaxies, extracted from the larger CALIFA sample, displaying either Type II ("down-bending") or Type III ("up-bending") surface brightness profiles. A correlation was found in the case of Type III galaxies. At lower masses, $\log(M/M_\odot) < 10$, a modest flattening in the $g' - r'$ colour, tends to be a common feature, together with a mild flattening of the O/H gradient, while at higher masses, both colour and O/H radial profiles display a pronounced flattening. The different behaviour detected for the Type III galaxies is tentatively attributed by Marino et al. (2016) to a downsizing effect, such that the higher-mass systems have already experienced a phase of inside-out growth, while for the smaller systems, an enhanced disk buildup phase is more recent or still ongoing.

5.4.2 An Analogy with Low Surface Brightness Galaxies?

It has been pointed out by some authors (Thilker et al. 2007; Bresolin et al. 2009b) that the structural parameters and the star-forming properties of outer spiral disks, such as the low mass surface densities and low star formation rates, resemble those observed in low surface brightness (LSB) galaxies. We can then ask the question whether this analogy extends to the chemical abundance properties. In particular, does a low star formation efficiency (Wyder et al. 2009) 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, in part due to observational challenges. Bresolin and Kennicutt (2015) measured H II region oxygen abundances for a sample of ten LSB spiral galaxies and investigated the presence of radial abundance gradients in this sample. They found that LSB galaxies do display radial abundance gradients that, 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, despite the similarities outlined above. This result suggests that the chemical evolution of LSB galaxies proceeds in a similar fashion to the high surface brightness galaxies, albeit at a slower pace due to the lower star formation rates, while the outer disks probably follow a different evolutionary path. The latter possibility is addressed in the following section.

5.5 The Evolutionary Status of Outer Disks

A variety of mechanisms can be invoked in order to explain the data presented in the previous section within a coherent picture of galactic chemical evolution. Unfortunately, the theoretical framework is, to a great extent, still lacking, since detailed modelling accounting for the gas-phase chemical abundances measured in the outer disks has not been developed yet. The relatively high metal enrichment observed in these H I-rich, low-star formation rate (SFR) regions of spiral galaxies suggests that some form of mixing mechanism, and perhaps more than one, should be responsible for the observed chemical abundance properties of the outer disks. This section presents some of the possible processes discussed in the literature that could redistribute metals produced in the main star-forming disk of spirals into their very outskirts, tens of kpc from the galactic centres. The effects of galaxy interactions and merging on the radial abundance gradients have already been introduced in Sect. 5.3.3, so that the focus will now be on mixing mechanisms that could affect, in principle, also isolated systems, but we should keep in mind that the chemical abundances in the outer disks could be sensitive to encounters that might have occurred in the distant past, as evidenced, for example, by the presence of warps in the H I envelopes.

The stellar radial migration process (Sellwood and Binney 2002; Roškar et al. 2008) does not affect the present-day abundance gradient of oxygen, since this element, whose abundance we trace with H II region spectroscopy, is produced by massive stars, which do not have sufficient time to migrate radially before ending their lives (Kubryk et al. 2015). Older tracers of ionized gas metallicity, such as planetary nebulae, can have a different behaviour (Magrini et al. 2016).

5.5.1 Flattening the Gradients

While some of the processes discussed below can explain the flattening of the H II region oxygen abundances observed in the outer disks, we start with the remark made by Bresolin et al. (2012), who suggested that the flat O/H distribution could simply be a consequence of relatively flat star formation efficiencies (Bigiel et al. 2010; Espada et al. 2011). Defining the star formation efficiency as $\mathrm{SFE} = \Sigma_{\mathrm{SFR}} / \Sigma_{\mathrm{HI}}$ (e.g. Bigiel et al. 2008), i.e. the ratio between the surface densities of star formation rate (inferred, e.g. from far-UV observations) and H I mass, we can approximate the gas-phase oxygen abundance per unit surface area of the disk, neglecting effects such as gas flows and variable star formation rates, as

$$\frac{\mathrm{O}}{\mathrm{H}} \sim \frac{y_{\mathrm{O}}}{11.81}\, t\, \frac{\Sigma_{\mathrm{SFR}}}{\Sigma_{\mathrm{HI}}} \propto \mathrm{SFE}, \tag{5.4}$$

where t is the duration of the star formation activity, since the amount of oxygen produced per unit surface area and unit time is the product of the oxygen yield (by mass) y_{O} and the star formation rate surface density. Then, according to (5.4), the flattened SFE radial profiles traced beyond the isophotal radius, relative to the behaviour in the inner disks, would result in a similarly flattened O/H radial gradient at large galactocentric radii, as observed. This appears to be consistent with the idea that the star formation activity at large galactocentric distances proceeds slowly enough for some metal mixing processes (discussed below) to efficiently erase or reduce chemical abundances, inhomogeneities and large-scale gradients.

Equation (5.4) can also be used to estimate that, given the low-star formation rates measured in the outer disks of spiral galaxies and the large H I content, the timescale necessary to reach the observed metal enrichment can be longer than the star formation timescale within an inside-out scenario for galaxy growth or even longer than a Hubble time, reinforcing the notion that the metallicities measured in outer disks exceed the values attainable by in situ star formation alone (see also Eq. (3) in Kudritzki et al. 2014 for an alternative calculation based on the closed-box model, leading to the same conclusion).

The link between SFE and O/H described above has been shown by recent tailored chemical evolution models to be able to reproduce the flattened gas-phase abundances in the outer disk of the Milky Way beyond 10 kpc from the centre (Esteban et al. 2013) and the flat oxygen abundance gradient in the outer disk of M83 (Bresolin et al. 2016, with an adaptation of the chemical evolution model by Kudritzki et al. 2015). This seems also to be consistent with chemical evolution models of the Milky Way in which the decreasing star formation efficiency with increasing galactocentric distance leads to a flattening of the metallicity gradients in the outer regions (Kubryk et al. 2015).

5.5.2 *Bringing Metals to the Outer Disks*

The transport of metals produced in the inner disks to large galactocentric radii appears to be necessary in order to explain the relatively high gas-phase metallicities observed in the extended disks of spiral galaxies. A number of different mechanisms have been discussed in the literature. The argumentation contained in the following section is rather speculative since, as already mentioned, a solid theoretical explanation for the chemical properties of extended disks is currently still missing. The mechanisms invoked can be broadly divided into two main categories: mixing and enriched infall. These are succinctly presented below, following in part Bresolin et al. (2009b, 2012) and Werk et al. (2011), to which the reader is referred to for a more in-depth discussion.

5.5.2.1 Mixing

Under this category we can include processes that can be effective in redistributing metals across galactic disks. Some examples are listed below:

- Outward radial flows originating from *viscosity* in the gas layer due, for example, to cloud collisions or gravitational instabilities (Lacey and Fall 1985; Clarke 1989) can produce flat gas-phase abundances in the outer disks (Tsujimoto et al. 1995; Thon and Meusinger 1998).
- Gas flows can also be driven by angular momentum redistribution from *non-axisymmetric structures*, i.e. bars and spiral arms. While stellar bars can affect the chemical evolution in the inner regions of galaxies (Athanassoula 1992; Cavichia et al. 2014), the overlap of spiral and bar resonances (Minchev et al. 2011) can affect the distribution and metallicity of stars at large galactocentric distances. The resonance associated with the corotation of the spiral pattern has been found to correlate with the radial position of breaks in the metallicity gradient by Scarano and Lépine (2013). This suggests that the gas flows occurring in opposite directions, inwards inside corotation and outwards beyond corotation, are connected to the different abundance gradients of the outer disks relative to the inner disks.
- Interstellar *turbulence* plays an important role in homogenizing the metallicity distribution in galactic disks (Scalo and Elmegreen 2004). What constitutes the main driving source, either stellar feedback or gravitational instability, is still uncertain (Krumholz and Burkhart 2016), although in the outer disks, which are characterized by very low star formation rates, it is unlikely that feedback from supernova explosions represents the main source of gas turbulence. The simulations by Yang and Krumholz (2012) indicate that turbulence driven by thermal instability is quite efficient in erasing kpc-scale metallicity gradients, on timescales that are on the order of a few orbital periods (a few 100 Myrs, Petit et al. 2015). Metals can be transported via convective motions of the gas over large distances, which leads to an equilibrium between star formation and turbulent mixing, making this an appealing mechanism for the explanation of the abundance properties of the extended disks of spirals.

5.5.2.2 Enriched Infall

The star formation and chemical enrichment histories of galaxies are profoundly affected by inflows and outflows of gas. Feedback-driven galactic winds eject a large portion of the metals produced in disk stars into the halos, the circumgalactic medium and the intergalactic medium (Kobayashi et al. 2007; Lilly et al. 2013; Côté et al. 2015) out to distances of the order of 100 kpc (Tumlinson et al. 2011; Werk et al. 2013). These outflows are crucial to explain, for example, the existence of the mass-metallicity relation observed for star-forming galaxies (Tremonti et al. 2004; Finlator and Davé 2008).

The gas that has been metal enriched by supernova explosions at early epochs and subsequently ejected from galaxies can later be re-accreted in a wind-recycling process (see, e.g. the models by Oppenheimer and Davé 2008; Davé et al. 2011). This re-accretion on the disk from the halo should take place preferentially in the outskirts, leading to an inside-out growth, on timescales on the order of a few dynamical times, $\sim$1 Gyr (Fu et al. 2013), necessary for the gas to cool down from the hot phase. Some evidence in support of this process has been presented recently by Belfiore et al. (2016) from the spatially resolved metal budget in NGC 628.

Fu et al. (2013) estimated the gas-phase metallicity of the infalling gas to be around 0.4× Solar for a Milky Way-type galaxy, which is in rough agreement with the observed metallicity of the extended disks. It is also worth pointing out that the metallicity of the circumgalactic medium at $z < 1$, as traced by Lyman limit systems, is bimodal, with a metal-rich branch peaking at a metallicity approximately 0.5× Solar, as shown by Lehner et al. (2013). According to these authors, this metal-rich branch could be tracing cool, enriched gas originating from galactic outflows and tidally stripped material.

The effects of an enriched infall process on galactic chemical evolution models have already been illustrated before. For example, Tosi (1988) showed how a metal-rich infall would affect the chemical composition of the outer parts of spirals, inducing a flattening of their abundance gradients, and estimated an upper limit for the infalling gas metallicity of 0.4× Solar from comparisons with the chemical abundances observed in the Milky Way. Figure 5.3 shows a model radial oxygen abundance gradient for the disk of M83, calculated with a galactic wind launched in the inner disk, following Kudritzki et al. (2015), but allowing for an inflow of metal-enriched gas with an oxygen abundance $12 + \log(\mathrm{O/H}) = 8.20$ (equivalent to 0.32× Solar). Such an enriched infall is required by the model to reproduce the gas metallicity observed in the extended disk of M83, with the flat distribution arising from the assumed constant star formation efficiency.

Minor Mergers Minor merger activity, as a source of cold gas leading to mass growth in galaxies, has also been proposed to be effective at chemically enriching the outer disks (López-Sánchez et al. 2015) and is included in this section because its effects could resemble those described above for enriched infall. Given the low accretion rates of star-forming galaxies due to mergers with low-mass satellites measured in the local Universe (Sancisi et al. 2008; Di Teodoro and Fraternali

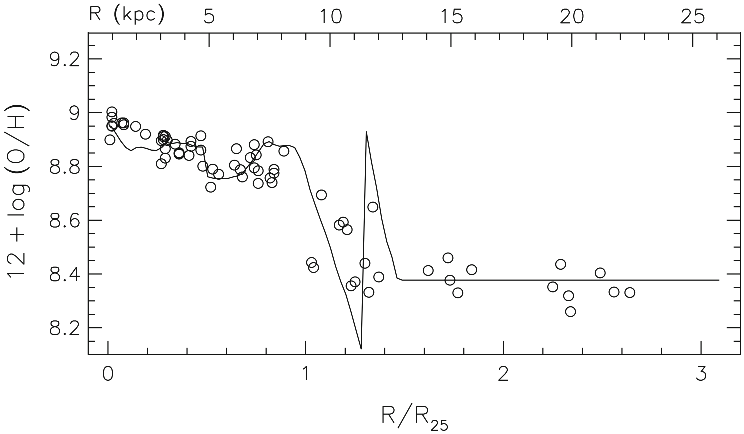

Fig. 5.3 Model radial oxygen abundance gradient for the disk of M83 (*continuous line*), calculated including an enriched gas infall, compared with the H II region metallicities (*open circles*) shown in Fig. 5.1 (Bresolin et al. 2016)

2014), this process is unlikely to be important for the chemical evolution of outer disks at the present time. However, higher merger rates in the past (around a redshift $z \simeq 2$) could have made this process a potential contributor to the accretion of metals in the outskirts of galaxies earlier on during their evolution (Lehnert et al. 2016). Numerical simulations by Zinchenko et al. (2015) also indicate that the stellar migration process induced by minor merging in Milky Way-type spirals cannot generate the flattening of the metallicity observed in the outer disks.

Different mechanisms can be invoked to explain the chemical abundance properties of outer disks. Among these are various mixing processes, including turbulence, and metal-enriched infall of gas from the circumstellar medium.

5.6 Conclusion

The outer disks of spiral galaxies remain a relatively unexplored territory in studies of the evolution of galaxies. This chapter has highlighted the somewhat unexpected attributes of the ionized gas chemical composition discovered in recent years in the outermost parts of galaxy disks, at least for systems with extended H I envelopes and ongoing star formation. At the same time, it is important to stress that metallicity information in the outer disks, gathered until now almost exclusively from H II regions, can provide crucial constraints for models of the chemical evolution of galaxies, considering that these are the most recently assembled regions of the disks according to the inside-out scenario. Future work will more firmly establish how common shallow or flat outer gradients with relatively high oxygen abundances are in spiral disks, which is relevant to ascertain the roles played by enriched galactic inflows and mixing mechanisms, such as turbulence, in regulating the chemical evolution of galaxies. Studies of the evolution of galaxies will benefit from probing the relationship between the gas-phase chemical abundances and the properties of the faint stellar populations present in these low surface brightness structures. A better understanding of the mechanisms leading to the formation of these extended structures and of the importance of the galactic environment in this context is highly desired. From the observational point of view, the combination of deep integral field spectroscopy with spatially resolved radio H I mapping for large samples of spirals will yield a better characterization of the relationship between gas, star formation, environment and metal production in determining the evolutionary status of present-day galaxies out to very large radii.

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