

Outer Spiral Disks as Clues to Galaxy Formation and Evolution

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Abstract: Recent studies of outer spiral disks have given rise to an abundance of new results. We discuss the observational and theoretical advances that have spurred the interest in disk outskirts, as well as where we currently stand in terms of our understanding of outer disk structure, ages, and metallicities.

Keywords: galaxies: abundances — galaxies: evolution — galaxies: spiral — galaxies: stellar content — galaxies: structure

1 Introduction

The importance of studying the faint outskirts of galaxies for our understanding of galaxy formation and evolution has become increasingly apparent in recent years. Due to their long dynamical timescales, galactic outer regions have retained the fossil record from the epoch of galaxy assembly in the form of spatial distribution, kinematics, ages, and metallicities of their stars (Freeman & Bland-Hawthorn 2002; Bullock & Johnston 2005). In addition, the secular evolution of spirals leaves the most conspicuous clues in the low density regions in galactic outskirts (Roškar et al. 2008a, 2008b; Martínez-Serrano et al. 2009; Sánchez-Blázquez et al. 2009; Schönrich & Binney 2009), providing an opportunity for testing scenarios of galaxy evolution using observations of the outer disks of spirals.

In this paper we look into recent advances in observational studies and numerical simulations of spiral disks, and the new insights they have provided into the processes of disk galaxy formation and evolution.

2 Recent Advances in Outer Disk Studies

The last decade has seen a growing interest in studies of the faint outer disks of spirals. The progress made in recent studies of disk outskirts has been brought together through a convergence of observational advances and theoretical breakthroughs. In this section we discuss both of these aspects.

2.1 Theoretical Advances

In 2002, Sellwood & Binney demonstrated that a star just outside (inside) the corotation radius — the radius at which a star's rotational velocity is equal to the pattern speed of the spiral arm — can be caught in the spiral arm resonance and transported inward (outward) while preserving the circularity of its orbit (Sellwood & Binney 2002). They also showed that transient spiral arms are at

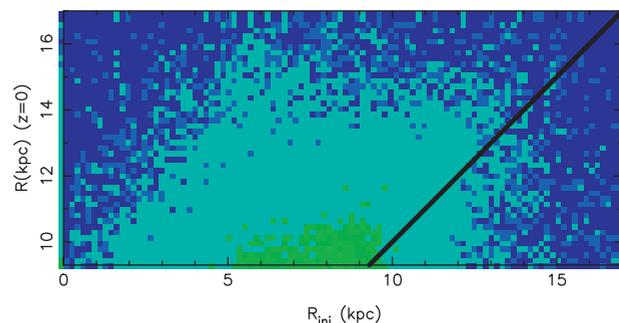


Figure 1 Final stellar galactocentric radius versus formation radius. From Sánchez-Blázquez et al. (2009).

the peak strength only for long enough to produce a single crossing from one side of the corotation to the other for each star. As a consequence, a large number of stars are scattered away from their birth radii (Figure 1). Recent years have seen a renewed interest in studies of stellar radial migration. Roškar et al. (2008b, hereafter R08b), Roškar et al. (2008a, R08a), Sánchez-Blázquez et al. (2009, SB09), and Martínez-Serrano et al. (2009, MS09) explore high-resolution, N-body simulations of disk formation and study the effects of stellar radial mixing on the properties of the final disk galaxy. A common feature of these models is a break in surface brightness at the radius of ~ 3 disk scale lengths, similar to what has been observed in a large fraction of spirals (Pohlen & Trujillo 2006).

The above simulations can be broadly divided into two classes: those that model an isolated disk galaxy (R08b; R08a) and those that study disk formation in the full cosmological context (SB09; MS09). The primary differences between the two sets of models can be summarized as follows:

- (i) While an R08b galaxy experiences breaks in both stellar surface density and surface brightness, SB09 and MS09 find no break in stellar surface density.

The latter suggests that the break in the surface brightness profile is a consequence of a change in stellar population properties across the break.

- (ii) A drop in the star formation rate (SFR), which in turn is due to a drop in the gas surface density, is the cause of the break in surface brightness in R08b. Similarly, the break in SB09 is due to a decrease in the star formation density per unit area, which itself originates from a decline in volume density of gas at the break radius. Interestingly, this coincides with the radius at which the gas disk begins to warp (although the causal relationship between the two effects has not been proven).
- (iii) In the R08b simulations, the outer disk is populated solely by the stars that migrated from the inner disk. Migration accounts for a majority (>60%) of stars found beyond the break in SB09 and MS09 galaxies, but star formation continues at a low level beyond the break.
- (iv) All of the above works find a minimum in the stellar age distribution at the break radius. In R08b this is a consequence of radial migrations only, whereas SB09 find that the minimum age at the break radius is seeded by a break in the star formation density and exists even if migration is suppressed.

Stellar radial migrations work towards weakening the correlation between metallicity and stellar age, which is a clear prediction of standard chemical evolution theory. R08a show that radial mixing can indeed explain the apparent lack of the age-metallicity relationship in the Galaxy; once the radial mixing has been taken into account, predictions agree with the mostly flat relationship observed in the Solar neighborhood. Furthermore, radial migrations have obvious consequences for the observed metallicity distribution function and metallicity gradient, the issue we discuss in more detail in Section 3.3.

In addition to the effects on the observable properties of the Milky Way, radial migrations could greatly influence our interpretation of resolved stellar population observations in external spirals. R08a show that significantly different star formation histories can be derived depending on whether migrations have been taken into account. The discrepancy is particularly large in the outermost disk, strengthening the importance of the outer regions of spirals as testbeds for the models of galaxy evolution.

While the exact predictions of these models are still to be tested, they could potentially dramatically change how we think about and model galaxy evolution.

2.2 Observational Advances

Light distribution in spirals has been studied for many decades using surface photometry. These integrated-light studies have shown that spiral disks generally follow an exponential surface brightness profile (de Vaucouleurs 1959; Freeman 1970) as well as that a fraction of galaxies exhibit profiles characterized by a broken exponential (van der Kruit 1979; Pohlen et al. 2000, 2002; de Grijs et al. 2001; Kregel et al. 2002; Kregel & van der Kruit

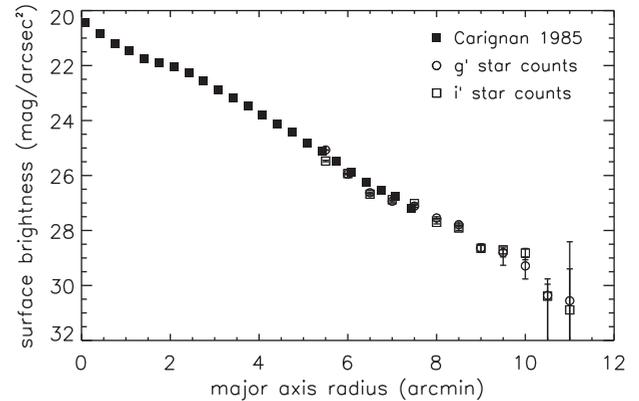


Figure 2 Surface brightness profile of NGC 7793. Full squares are surface photometry data from Carignan (1985). Open symbols are effective surface brightness measurements derived from star counts. From Vlajić et al. (2009).

2004; Pohlen & Trujillo 2006). However, although a direct method, surface photometry suffers from many technical difficulties at levels below $\mu_R \approx 27 \text{ mag arcsec}^{-2}$. These include difficulties of data flatfielding (Pohlen et al. 2002), zodiacal light (Bernstein et al. 2002), diffuse Galactic emission (Reynolds 1992; Haikala et al. 1995), light scattered by the HI disk (Bland-Hawthorn et al. 2005), and effects of extended tails of the Point Spread Function (de Jong 2008). These limit the application of surface photometry for studies of the extremely low surface brightness regions. It has been acknowledged that star counts offer a superior method for tracing faint stellar populations in the outskirts of galaxies. By resolving individual stars and calculating the effective surface brightness from star counts, it is possible to reach 3–5 mag arcsec^{-2} deeper than possible with surface photometry (Pritchet & van den Bergh 1994; Bland-Hawthorn et al. 2005; Irwin et al. 2005; de Jong et al. 2007; Ferguson et al. 2007). An example is shown in Figure 2; in NGC 7793, the star counts profile significantly increases the known radial extent of the disk.

The most challenging aspect of studying outer disk light profiles is the need to determine the background level that is then subtracted from the raw profile in order to calculate the true star counts or surface brightness profile of a galaxy. In the case of surface photometry this is manifested through difficulties in deriving accurate estimates of sky brightness. When resolved stellar photometry is used instead to study the outskirts of spirals, the task translates into how to reliably evaluate the number of unresolved faint background galaxies that are mistakenly included in stellar catalogues. The challenge is particularly difficult when information on number counts as a function of color (and not only magnitude) is required. This problem can be — and is being — partially solved by using space-based facilities with superior seeing, or ground-based instruments with adaptive optics capabilities. While difficulties in surface photometry observations pertain to the nature of the observations themselves, star-galaxy separation, which hinders resolved star observations, is limited by our knowledge of galaxy number counts and ability to reliably distinguish between the two classes of objects.

3 Outer Disk Structure, Ages, and Metallicities

3.1 Structure of Outer Disks

A view of a simple exponential describing the light profile in spirals (Freeman 1970) has evolved over the decades to include galaxies in which an inner profile is followed by an outer, steeper one (a.k.a. broken, truncated, sub-exponential profiles; van der Kruit 1979; Pohlen et al. 2000, 2002; de Grijs et al. 2001; Kregel et al. 2002; Kregel & van der Kruit 2004; Pohlen & Trujillo 2006) as well as the galaxies with a shallower exponential following the inner disk light profile (a.k.a. upbending, anti-truncated, super-exponential profiles; Erwin et al. 2005). Both surface photometry and star counts confirm the diversity in outer disk structure (Bland-Hawthorn et al. 2005; Irwin et al. 2005; Barker et al. 2007; de Jong et al. 2007; Ferguson et al. 2007). However, thirty years after its discovery, the origins of this diversity are still not known. Interactions and minor mergers have been proposed to explain super-exponential profiles; this is supported both by simulations (Peñarrubia et al. 2006; Younger et al. 2007) and by the finding that these types of profiles are more common in high-density environments (Pohlen & Trujillo 2007). Scenarios proposed to explain sub-exponential profiles can broadly be classified into those in which the break is seeded during the galaxy formation processes (and marks the radius corresponding to the maximum angular momentum of the proto-galaxy; van der Kruit 1987), and those in which a break in surface brightness is a consequence of galaxy evolution (having to do with the threshold for star formation and/or secular evolution due to spiral arms or bars; Kennicutt 1989; Schaye 2004; Debattista et al. 2006; Elmegreen & Hunter 2006; Foyle et al. 2008; Roškar et al. 2008b; Sánchez-Blázquez et al. 2009). Van den Bosch (2001) combined the two scenarios to propose a picture in which the distribution of cold gas is truncated to reflect the maximum angular momentum of the collapsed cloud, while the break in the stellar light profiles points to the presence of a star formation threshold. The ability of some spiral disks to retain the exponential light profile out to very large distances (e.g. NGC 300; Bland-Hawthorn et al. 2005) also remains a puzzle; in fact, producing an extended, purely exponential disk seems to be the most challenging requirement for the simulations of disk formation and evolution.

3.2 Ages of Outer Disks

Age behavior in spirals is very challenging to discern in galaxies too distant for the full star formation history (SFH) to be modeled. This is largely due to the age-metallicity degeneracy and the lack of indicators that are primarily age-sensitive. Rough overall age and the dominant stellar population can, however, be relatively easily determined from the color-magnitude diagram, and resolved stellar photometry studies of nearby spirals find both young and old outer disks. For instance, Davidge (2006, 2007) finds young and intermediate-age stars at large galactocentric distances (~ 7 disk scale lengths) in

NGC 2403 and NGC 247, in agreement with an inside-out growing stellar disk (Ryder & Dopita 1994; Naab & Ostriker 2006). On the contrary, M33, NGC 300, and NGC 7793 seem to harbor old outer disks with red giant branch stars as a dominant stellar population (Barker et al. 2007; Vlajić et al. 2009, 2010).

As briefly mentioned in Section 2.1, models of galaxy formation that include the effects of secular evolution predict a minimum stellar age at the break radius and a positive age gradient in the outer disk.

SB09 interpret this 'U'-shaped age profile as being a consequence of the break in star formation density, whereas in the R08b simulations the particular shape of the age gradient arises exclusively due to stellar migrations. Two recent observational studies support these theoretical predictions for the shape of the age gradient.

Bakos et al. (2008) derive surface brightness and color profiles from surface photometry of a sample of 85 late-type galaxies from the SDSS data. They find that for galaxies which exhibit a break in their surface brightness profiles, the $g' - r'$ color profile has a minimum (i.e. bluest color) at the break radius and becomes redder in the outer disk, mimicking the shape of the age gradient described above. SB09 find a similar color gradient in their simulated disk and confirm that the color profile indeed mirrors the age (and not metallicity) gradient.

For galaxies that are sufficiently close, stellar color-magnitude diagrams can be used to model the detailed SFHs. Barker et al. (2007) use this approach to derive SFHs of three fields in the outer disk of M33 and find that beyond 9 kpc the mean stellar age is an increasing function of radius. Similarly, Williams et al. (2009) reconstruct SFHs for four inner disk fields in M33. Their fields span the distances from 1 to 6 kpc and exhibit mean ages that decrease from the center of the galaxy outward. The two results point to an overall picture in which the age gradient has a minimum at the break radius (~ 9 kpc in M33; Ferguson et al. 2007), similar to what has been predicted by R08b, SB09, and MS09.

3.3 Metallicities of Outer Disks

Traditional inside-out models for disk galaxy formation (Ryder & Dopita 1994; Naab & Ostriker 2006) predict negative abundance gradients in spirals. Surface density, yield, and star formation all decline with radius, resulting in metallicity distribution that is more metal-rich in the central parts and decreases progressively towards the outer disk. However, there is a growing body of evidence suggesting that most spirals exhibit a flattening of their metallicity gradient in the outermost disk. Observationally, the strongest cases have been made for the Galaxy (Andrievsky et al. 2004; Yong et al. 2006; Carraro et al. 2007; Pedicelli et al. 2009), M83 (Bresolin et al. 2009), and potentially NGC 300 (Vlajić et al. 2010), although the effect has been reported in a few additional spirals. On the other hand, an apparent lack of flattening is observed in NGC 7793 (Vlajić et al. 2009) and possibly M33 (Barker et al. 2007).

Radial migrations offer a possible explanation for the shallower slope of the outer disk abundance gradients. R08a find that the slope of the stellar abundance gradient decreases with increasing age of the stellar population, a result which is confirmed in the SB09 work. This, combined with the age behavior described above, results in the mean overall gradient which flattens in the outer disk (at ~ 12 kpc in SB09).

4 Conclusions

Thanks to a confluence of exciting new results from both observational and theoretical work, outer spiral disks have in recent years become a fast-growing research area. While more deep stellar photometry is necessary in order to test the predictions of a growing body of numerical simulations of disk formation and evolution, our current understanding can be summarized as follows:

- (i) The origin of the diversity in outer disk structure remains a puzzle. While scenarios have been proposed to explain sub- and super-exponential profiles, the full picture, which self-consistently explains the existence of all three types of light profiles, is lacking.
- (ii) Radial migrations potentially play a significant role in the evolution of disk galaxies; this could have profound consequences on how we model galaxy evolution, in particular the chemical evolution in spirals.
- (iii) Star counts have been shown to be a superior method for probing faint outer disks in individual galaxies compared with traditional surface photometry.
- (iv) Age behavior in disks is very challenging to determine from resolved stellar photometry. However, a small number of studies seem to indicate that in the case of galaxies with sub-exponential profiles, the minimum stellar age is observed at the break radius, in agreement with simulations of radial mixing in spirals.
- (v) A metallicity gradient that flattens in the outermost regions seems to be a general feature of spiral disks. However, some spirals experience a single-slope negative gradient with no flattening.

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