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**Spontaneous and Stimulated Star Formation in Galaxies:
 Ultraviolet Limits on Star Formation Thresholds and
 Optical Constraints on Lambda-CDM Cosmological
 Simulations of Galaxy Formation.**

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Abstract.

We present recent results from several on-going studies: The first addresses the question of gas-density thresholds for star formation, as probed by the outer disks of normal nearby galaxies. The second concerns the observational evidence for the existence of gravitating non-luminous (GNL) galaxies, as predicted by most recent simulations of galaxy formation in Lambda-CDM cosmologies. We find that (1) If star formation is traced by far-ultraviolet light, then there is no evidence for a threshold to star formation at any gas density so far probed, and (2) there is no evidence for GNL galaxies gravitationally interacting with known optical systems based on the observations (a) that there are no ring galaxies without plausible optically visible intruders, (b) all peculiar galaxies in the Arp Atlas that are bodily distorted have nearby plausibly interacting companions, and (c) there are no convincingly distorted/peculiar galaxies within Karachentsev's sample of more than 1,000 apparently/optically isolated galaxies.

1. Introduction

Galaxies continue to surprise us, both in their observed structure and by their inferred evolution. Some of these surprises come from moving to new wavelengths and re-observing old friends; while other surprises come staying at familiar wavelengths but looking at the galaxies from a somewhat new perspective or in a slightly revised context.

With the launch of the GALEX satellite into low-Earth orbit on April 28, 2003 it has become possible to image a large number and a wide range of different types of galaxies at largely unexplored wavelengths: in the near and far ultraviolet. Given the high sensitivity of the detectors and the very low sky background (especially in the far ultraviolet channel) it is possible to see features in the ultraviolet out to surface brightness levels unequalled by ground-based optical observations. Moreover, the wide (one-degree) field of view of GALEX also maximizes the possibility of serendipitous discovers, of which there have been many.

2. Radially Extended Star Formation

All of the above aspects of GALEX contributed to the “discovery” of *extended ultraviolet* (XUV) disks around a number of nearby spirals. Prime examples, found early in the mission are M83 (Thilker *et al.* 2005) and NGC 4625 (Gil de Paz *et al.* 2005). A comparison of the optical image of the compact, one-armed spiral NGC 4625 with its significantly more extended, and multi-armed UV counterpart image is shown in Figure 1.

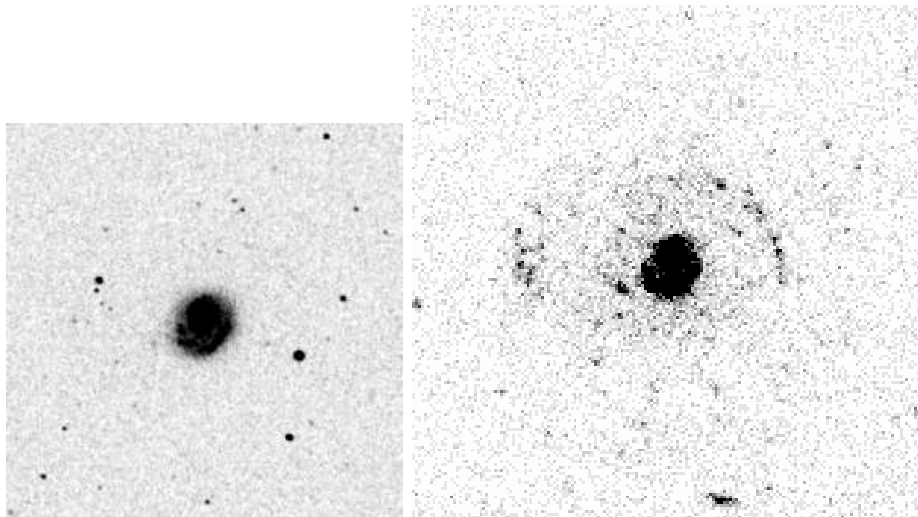


Figure 1. NGC 4625. Right panel shows the optical image of the galaxy, while the left panel shows the NUV (GALEX) of this same galaxy where the extended UV disk of star formation is clearly highlighted

2.1. Pre-Discoveries and Thresholds

While these features are striking, they should not have come as a surprise (although they did) as they are not unheralded. For instance, based UV imaging data obtained from a balloon-borne experiment (SCAP 2000) Donas et al. (1981) asked the question “How Far Does M101 Extend?” Clearly they were seeing extended UV features in the outer disk of a well known nearby galaxy. And later Ferguson et al. (1998), announced “The Discovery of Recent Star Formation in the Extreme Outer Regions of Disk Galaxies” based on deep H α surveys of three nearby late-type galaxies: NGC 0628, NGC 1058 and NGC 6946. And all of this might have been seen to be a natural consequence of the discovery of extended HI disks around many galaxies (e.g., NGC 2915, Muere et al. 1996) except perhaps for the interesting interpretive paper by Martin & Kennicutt (2001) which seemed to put an end to star formation in the outer disks of galaxies by titling their paper “Star Formation Thresholds in Galactic Disks.” With hindsight, which we all now possess, it might have been more robust to have added “as Traced by HII Regions” to the title.

2.2. Ultraviolet Data

Recently, using GALEX ultraviolet imaging data, Boissier et al. (2007) have re-examined the correlation of gas density with star formation (*as traced by FUV/NUV light*) and have come to very different conclusions regarding the existence of any threshold to star formation at low gas densities. As can be seen in Figure 2 the left panel shows the run of star formation rates as a function of total gas density for a combined sample of 43 galaxies. The star formation rate is based on extinction-corrected UV surface brightness obtained by the GALEX satellite and the total gas density combines neutral and molecular hydrogen contributions. The right panel shows a selection of individual galaxies where the run of UV and the H α star formation rates with surface density of gas are intercompared on an individual basis. Clearly there is a difference. No truncation and no threshold is apparent in the UV data. The surface density of star formation as traced by hot, blue stars (which may or may not) include O stars (which power the brightest HII regions) is continuous with the gas surface density, to the limits of both surveys.

The hard cut-off in H α has been challenged, of course, by Ferguson et al. (1988), but it may also be that other factors are in play. In the outer parts of galaxies we may be seeing small number statistics force the mass function of the molecular clouds down to a mass level that while they can support star formation they are not individually large enough to produce even a single O star capable of ionizing the surrounding medium. The plane thickness may have grown so much, or the intercloud separation may be so large that the star formation regions are density-bounded and that large fraction of the UV radiation is leaking out before it can produce a detectable HII region or that the radiation that is intercepted is only reradiated at a very low emission measure and perhaps and widely distributed. Very compact HII regions have been found in the XUV disk of M83 and they are consistent with single-star ionization (Gilde Paz et al. 2005). Studies are underway to probe deeper and to lower surface brightness levels in search of any stray radiation.

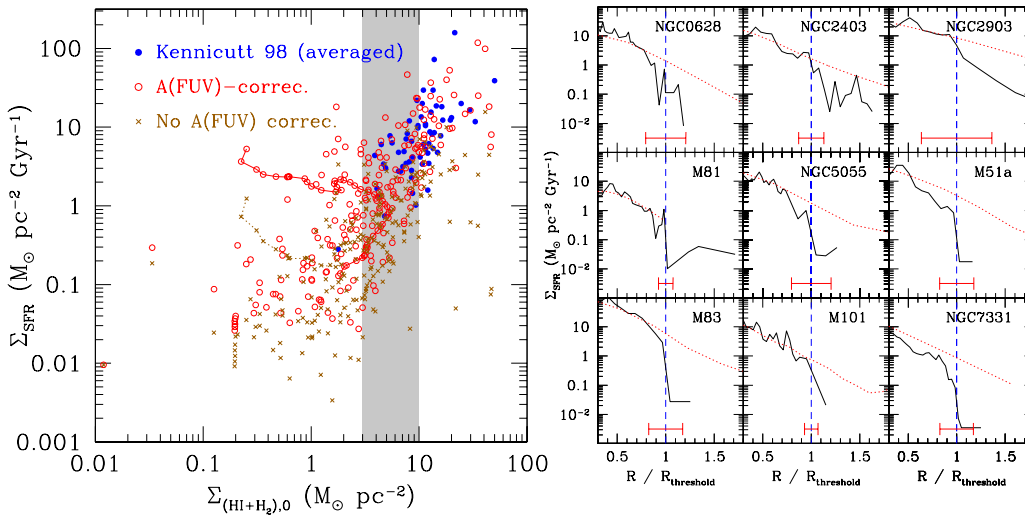


Figure 2. The left panel shows the radial drop-off of star formation rates as a function of gas density for ** galaxies as reproduced from Boissier et al. (2007). The vertical grey zone shows the gas-density where the star-formation threshold of Martin & Kennicutt (2001) is expected. For the UV data no threshold is observed. The right panels shows an intercomparison of UV star formation rates (dotted lines) and H α star formation rates (solid lines) as a function of radius (scaled to the Martin-Kennicutt threshold.) Again, the UV star formation shows no sign of any thresholding at any gas density plotted.

3. Gravitating Non-Luminous (GNL) Galaxies

Most contemporary models of structure formation within the framework of a *Lambda*-CDM cosmology predict a steep power-law increase of lower mass galaxies fainter than L^* (e.g., Kravtsov, Gnedin & Klypin 2004). Most of the satellites are deemed “missing” because they not seen in optical surveys. This has led to the speculation that they are currently somehow devoid of baryons, and thus invisible by construction. Invisible but not undetectable. The presence of *Gravitating Non-luminous* (GNL) galaxies can in principle (and in practice) be inferred (and seen) by their gravitational interactions with other nearby (visible) galaxies. Below we explore a few such tests for their presence ... or absence.

3.1. Ring Galaxies

Twenty years ago Arp & Madore (1987) published a catalog and photographic atlas of peculiar galaxies based on a visual inspection of over 94,000 optical images of southern-hemisphere galaxies. More recently Madore, Nelson & Petrillo (2007 in prep) extracted from that a pure sample of about 100 ring galaxies (see Figure 3 for a sampling). According to models by Theys & Spiegel (1976) and by Lynds & Toomre (1976) they can be explained by galaxy-galaxy interactions, fine-tuned to be head-on collisions between a disk galaxy and a lower-mass intruder. The ring galaxies culled from the Arp-Madore Catalogue were listed by those original discoverers because of their ring morphology not because they

did or did not have companions. However, it is gratifyingly strong confirmation of the theory that virtually all of the rings also have adjacent (line of sight) companions (many of which already have redshifts confirming their physical as well as apparent association with the rings.) These companions are plausible colliders, based on their apparent proximity and being only a diameter or two from the ring itself.

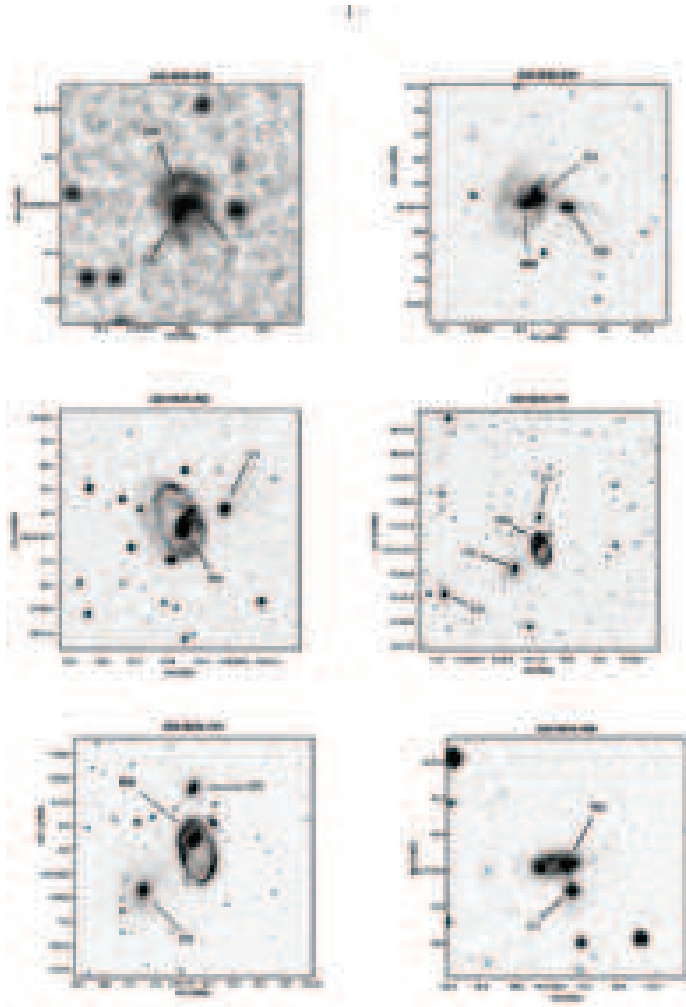


Figure 3. Examples of ring galaxies and their adjacent companions from the soon to be published atlas of Madore, Nelson & Petrillo (2007)

While this is all good news for the theory of ring formation in specific, it is not so good news for the theory of galaxy formation in general. Without a single convincing example of an isolated ring, one obvious conclusion is that GNL galaxies do not exist in the numbers predicted by theory. While it may be counter-argued that ring galaxies require such peculiar circumstances for their formation (mass ratios, orbital parameters and galaxy types, etc.) and that they

can only arise from a collision involving concentrated *baryonic* satellite intruders for their formation, the same cannot be said for collision-induced peculiarities in general. The CDM simulations predict the observed number of optical galaxy only at one mass. Above and below this there is a divergence at all masses between theory and observation, reach more than a factor of 10 discrepancy at the faintest end. Whether it is high-mass or low-mass companions that are being looked for in GNL-galaxy interactions they are predicted to be there at the level of factors more than their optical counterparts rather than occasionally occurring at very low levels of incidence, as appears to be the case.

3.2. Arp Peculiar Galaxies

Turning back to the time at which the original *Atlas of Peculiar Galaxies* was published (Arp 1966) it is fair to say that the topic of peculiar galaxies was still in its formative stages and that the sample illustrated was not premised upon their being or not being nearby galaxies to qualify them to be included in the Atlas. Indeed by modern standards many of the galaxies in the *Atlas* are not now considered to be particularly peculiar at all (*e.g.*, low-surface-brightness galaxies [ARP 001-004], dwarf irregular galaxies [ARP 005-006], and certain alignments in small groups and clusters [ARP 311-332]). Rare does not necessarily mean peculiar, but the *Atlas of Peculiar Galaxies* did include many rare types of objects. Our point here is however that of the 338 objects that are included in the *Atlas* because the galaxy in question is bodily distorted, is considerably asymmetric or has extended tails, the vast majority of those have very nearby companions that can easily be implicated as the source of the interaction and distortion. It is the absence of *isolated* peculiar galaxies that is in itself noteworthy. Clearly the vast majority of peculiarities seen as bodily deformations of the galaxy in question can be explained by interactions with nearby optical companions. And this simple fact leaves no room (and no evidence for) bodily deformed galaxies resulting from their interaction with gravitating non-luminous (GNL) galaxies (*i.e.*, pure dark-matter halos).

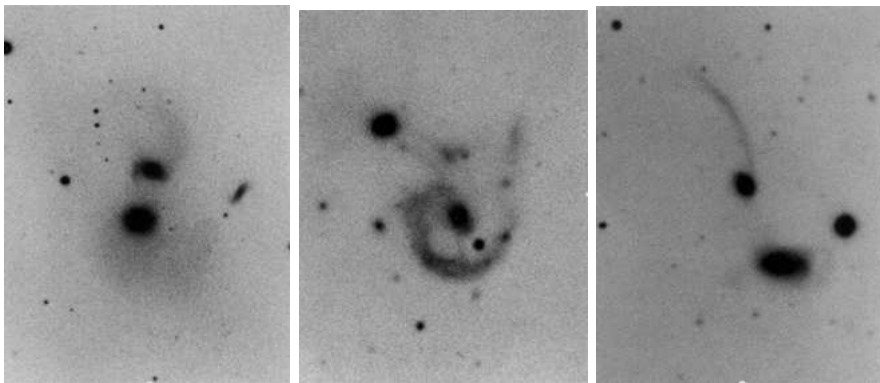


Figure 4. Arp 172 (left), Arp 107 (center) and Arp 173 (right) typify the types of bodily distorted galaxies in the Arp Atlas of Peculiar Galaxies that almost without exception have obvious interactions on-going between two optically visible galaxies

3.3. Karachentsev Isolated Galaxies

There is an alternative path to follow here. Karachentsev (1988) published a list of 1,000 galaxies that are optically isolated from other comparable-sized (optically visible) galaxies. This, of course, is not to say that apparently isolated cannot and do not have GNL galaxies of comparable (or even larger) sizes orbiting and interacting with them. However this catalog would suggest that this is not the case. With complete certainty we can say that out of the entire sample of optically isolated galaxies there are no examples of Arp-like bodily-distorted systems.

There are a handful of isolated galaxies that are peculiar to some lesser degree. But even this is to be expected without having to invoke GNL galaxies; mergers will deplete the apparent population of visible interactors while still leaving evidence of the collision in the form of tidal debris or lingering asymmetries. For example, even a cursory examination of the 2MASS near-infrared image of KIG 0022 (an object that has large ‘tidal’ arms in the optical) shows that it has a double nucleus; presumably the result of a recent merger of two (previously) visible galaxies. Details of these samples and their analysis will be given in a forthcoming paper (Madore, Petrillo & Nelson 2007).

4. Conclusions

Using UV light as a tracer for star formation, FUV and NUV imaging observations of nearby galaxies using the GALEX satellite show a smooth and monotonic decline of star formation with total gas surface density. No thresholding of star formation is visible in this sample, at these projected surface densities.

The summary observations of peculiar galaxies viewed in the context of *Lambda*-CDM simulations are as follows: (1) All cataloged ring galaxies have plausible colliders that are optically visible. (2) All peculiar galaxies (in the Arp Atlas) that are bodily deformed have visible nearby companions that are plausibly responsible for the interaction-induced deformities. (3) Virtually all isolated galaxies are not peculiar, distorted or interacting to any noticeable degree.

The peculiar galaxy study leads to the following general conclusions: (1) No ring galaxy is being produced from a head-on collision between a spiral and pure dark-matter GNL galaxy (2) No bodily deformed galaxies are the result of collisions and/or near encounters between optical and pure dark-matter GNL galaxies. (3) Optically isolated galaxies show no signs of bodily interactions with pure dark matter GNL galaxies.

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