The nature of extremely red galaxies in the local universe

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ABSTRACT
We investigate the nature of extremely red galaxies (ERGs), objects whose colours are redder than those found in the red sequence present in colour–magnitude diagrams of galaxies. We selected from the Sloan Digital Sky Survey Data Release 7 a volume-limited sample of such galaxies in the redshift interval $0.010 < z < 0.030$, brighter than $M_r = -17.8$ (magnitudes dereddened, corrected for the Milky Way extinction) and with $(g - r)$ colours larger than those of galaxies in the red sequence. This sample contains 416 ERGs, which were classified visually. Our classification was cross-checked with other classifications available in the literature. We found from our visual classification that the majority of objects in our sample are edge-on spirals (73 per cent). Other spirals correspond to 13 per cent, whereas elliptical galaxies comprise only 11 per cent of the objects. After comparing the morphological mix and the distributions of Hα/Hβ and axial ratios of ERGs and objects in the red sequence, we suggest that dust, more than stellar population effects, is the driver of the red colours found in these extremely red galaxies.

Key words: galaxies; fundamental parameters – galaxies: photometry – galaxies: spiral.

1 INTRODUCTION
The bimodality is a conspicuous feature of optical colour–magnitude diagrams (CMDs) of galaxies in the local and distant universe (e.g. Strateva et al. 2001; Kauffmann et al. 2003; Wiegert, de Mello & Horellou 2004; Mateus et al. 2006; Nicol et al. 2011), and is able to provide interesting constraints on how galaxies evolve (Asari et al. 2007; Mateus et al. 2007; Taylor et al. 2011). It presents two major features: the red sequence (RS), populated mostly by passive, ‘dead’, galaxies, in general ellipticals, lenticulars and passive spirals, and the blue cloud, containing spirals and irregulars with ongoing star formation activity. The region between these two major features is often called the green valley (e.g. Baldry et al. 2004; Mendez et al. 2011; Gonçalves et al. 2012). The colour bimodality has an environmental component: while the blue star-forming galaxies tend to populate low-density regions, RS galaxies are often found in clusters and rich groups (e.g. Oemler 1974; Dressler 1980; Postman & Geller 1984).

The position of a galaxy in a CMD is often interpreted in terms of its evolutionary status and, in particular, on whether or not, or at which level, it is still forming new stars. Indeed, spectrophotometric models suggest that, after $\sim$1–2 Gyr, a blue galaxy which had its star formation stopped by internal or environmental mechanisms migrates from the blue cloud to the RS (e.g. Bell et al. 2004; Blanton 2006; Gabor et al. 2010), crossing the green valley. While most of these galaxies would have already changed their morphology from late-type to early-type galaxies, a significant number of spirals can also be found in the RS (e.g. Bamford et al. 2009; Skibba et al. 2009; Masters et al. 2010b; Robaina et al. 2012; Tojeiro et al. 2013), especially at high redshifts (Bundy et al. 2010; Bell et al. 2012). These results suggest that colour is much more sensitive to environment than morphology, with colour transformations from blue to red occurring on time-scales much shorter than those of morphological transformations.

But a close inspection of optical CMDs of galaxies in the local universe show many galaxies with colours above those of the RS. Why are these galaxies so red? Is this due to old, probably metal-rich stars? Is this due to dust? Indeed, dust in the interstellar medium of galaxies, besides absorbing part of the optical light, may redder galaxy colours. There is, actually, an age–extinction degeneracy: a galaxy possessing high extinction can have colours similar to an older object without extinction (Worthey 1994, de Meulenaer et al. 2013). Dust affects mostly star-forming objects (e.g. Alam & Ryden 2002, Masters et al. 2010a), because star formation occurs in dusty molecular clouds in discs. The effects of dust on the observed properties of spirals, including colours, have been studied as a function on their inclination (e.g. Cunow 1992; Giovanelli et al. 1994; Tully et al. 1998; Masters, Giovanelli & Haynes 2003; Masters et al. 2010a), and, as expected, are more significant for edge-on spirals.

The objective of this paper is to address the nature of the extremely red galaxies (ERGs) – those above the ordinary RS of passive galaxies – in the local universe. We want to know what galaxies are these, their morphology, and why their colours are so...
red, if due mainly to stellar populations or to dust. We approach this problem by selecting a sample of nearby ERGs from the Sloan Digital Sky Survey (SDSS) Data Release 7 (Abazajian et al. 2009) and visually examining their images. We also compare our visual classification with those produced by the Galaxy Zoo project (Lintott et al. 2011) and by the automated support vector machine (SVM) algorithm of Huertas-Company et al. (2011).

It is worth mentioning that our ERGs are not the same as the extremely red objects (EROs), found in optical and in infrared surveys at larger redshifts and often associated with galaxies dominated by old populations or dusty starbursts (e.g. Cimatti et al. 2004; Kong et al. 2009) although some ERGs, if at high redshift, could be classified as EROs.

The outline of this paper is as follows. We present, in Section 2, the SDSS sample of ERGs compiled in this work. Section 3 describes the results of our visual classification and a comparison with classification obtained by other authors. In Section 4, we discuss the origin of the extreme colours of these galaxies. Finally, in Section 5, we summarize our main findings.

2 THE DATA

To investigate the nature of the ERGs in the nearby universe, we have selected objects classified as galaxies and with measured spectroscopic redshift from the SDSS Data Release 7 (Abazajian et al. 2009), in the redshift interval $0.010 < z < 0.030$ and brighter than $r = 17.77$ (the spectroscopic magnitude limit). This selection criterion was adopted for two reasons: first, the low redshift is required for having galaxies close enough and with relatively large apparent size to assure a good resolution for visual inspection of the images, minimizing morphological misclassifications; secondly, the redshift interval should be narrow enough to avoid $k$-corrections and evolutionary effects affecting the galaxy colours.

We also imposed the following photometric quality flags in the galaxy selection: NCHILD = 0, not BRIGHT, not SATURATED, not SATUR_CENTER, in order to minimize the number of objects with image defects returned by the query.

This selection leads to 31 067 galaxies. The CMD, $(g - r)$ versus $M_r$, of the selected galaxies is shown in Fig. 1. All apparent magnitudes here are of the model type, which should give more reliable colour measurements than other types of magnitudes, and are corrected by Galaxy extinction (dereddened magnitudes). Absolute magnitudes were computed assuming a cold dark matter cosmological model with $H_0 = 72$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.3$ and $\Omega_{\Lambda} = 0.7$. We did not apply any $k$-correction in the estimation of absolute magnitudes because, in the redshift interval considered here, they are very small and even smaller than their own uncertainties (Blanton & Roweis 2007). The CMD shown in Fig. 1 presents a conspicuous RS ($g - r \sim 0.8$), as well as the blue cloud ($g - r \sim 0.4$).

We consider here as ERGs those above the line

$$(g - r) = 0.81 - 0.03(M_r + 18.1067)$$

in the CMD; this is the line above the RS in Fig. 1. We adopt here a volume limited sample, by considering only galaxies with luminosities above $M_r = -17.76$. There are 468 objects above the line in our volume-limited sample.

It is important to verify whether the extreme colours found here are real or outliers/artefacts in SDSS. Indeed, an examination of the

\footnote{http://www.sdss.org/dr7/algorithms/photometry.html}
in SDSS area, not presenting any relevant bias with respect to Galaxy extinction.

The results of the next sections are relatively robust with respect to the definition of ERGs. For example, considering a sample of galaxies in Fig. 1 with \((g - r) > 0.9\), we obtain qualitatively the same results described in the next sections.

3 MORPHOLOGICAL ANALYSIS

To investigate the morphology of the galaxies in our ERG sample we adopted three procedures: (a) direct visual inspection of images; (b) comparison with Galaxy Zoo classification (Lintott et al. 2011) and (c) comparison with Huertas-Company et al. (2011) automated classification. The results are presented in the next subsections.

3.1 Classification by visual inspection

All ERG images were examined with the SDSS task Navigator, which provides composite colour images of SDSS objects. Each image was then classified in one of the following classes: (1) spiral galaxy seen edge-on, (2) spiral galaxy with visible spiral arms or noticeable inclination, (3) elliptical or lenticular galaxy, (4) merger/interacting/irregular object and (5) image with defects, with bad segmentation or with Milky Way stars projected on to the central parts of their image, affecting the galaxy colours. Example images for those five classes are given in Fig. 3.

Despite the low redshift of this sample, the classification of more compact galaxies is somewhat uncertain; for example, it is sometimes difficult to distinguish a face-on compact spiral blurred by the seeing from an elliptical or lenticular galaxy. Edge-on spirals and lenticulars are also difficult to distinguish, although sometimes evidence for star formation can be seen in the image. A face-on lenticular and an elliptical are also hard to distinguish; although our class 3 is dominated by elliptical galaxies, it probably also contains some lenticulars. Merger here comprises a large class of objects with irregular morphology due mostly to interactions and mergers. The ‘defects’ (class 5) include all those images which, for some reason, are not useful for our analysis.

The results of our classification are summarized in Table 1. By far, most of the ERGs in our sample are edge-on objects \((73 \pm 4\)%). The fractions of (not edge-on) spiral and elliptical plus lenticular galaxies are roughly similar, \(\approx 12\%\), about six times smaller than that of edge-on discs. We have assumed Poissonian errors here and throughout this paper.

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3.2 Classification by Galaxy Zoo

We cross-checked our classification with that provided by the Galaxy Zoo project and discussed in Lintott et al. (2011). This ‘citizen science’ project provides morphological classifications (actually probabilities that a galaxy is in a given morphological class) of nearly 900 thousand galaxies produced by hundreds of thousands of volunteers. This classification has proven useful in many analyses requiring morphological information (e.g. Bamford et al. 2009; Darg et al. 2010; Schawinski et al. 2009; Skibba et al. 2009; Masters et al. 2011; Hoyle et al. 2012).

There are many potential biases that can affect the morphological classifications produced by Galaxy Zoo, which were discussed by Bamford et al. (2009) and Lintott et al. (2011). These biases occur because visual classifications are affected by the brightness and apparent size of the galaxies in the sample: naturally, smaller and fainter objects are more difficult to classify than larger and brighter objects. As a consequence, for each object the Galaxy Zoo team provides two types of classification. The first one comprises the classes elliptical (E), edge-on spirals (S edge-on), spirals with visible arms (S other; a combination of Galaxy Zoo classes clockwise spirals, CW, and anticlockwise spirals, ACW), Merger and Don’t Know, with the fraction of volunteers votes for each class (note that the ‘edge-on’ category from Galaxy Zoo includes both proper edge-on spirals and also those without clear arms). The second type comprises debiased votes, where the classification bias mentioned above is statistically corrected for (see appendix A of Bamford et al. 2009, for details). The debiased classes are designated as \(E_d\) for ellipticals and \(S_d\) for spirals (CW, ACW and edge-on).

We adopted the maximum probability to ascribe a morphological type to a galaxy. Out of 416 objects in our sample, there are 409 and 408 with ordinary and debiased classifications in Galaxy Zoo, respectively. This classification, summarized in Table 2, also demonstrates that edge-on objects are dominant among ERGs, comprising \(65 \pm 4\)% percent of the sample. Considering the debiased votes, the table indicates that about 1/4 of the ERGs were classified as ellipticals whereas 3/4 were classified as spirals.

3.3 Classification by SVM

Huertas-Company et al. (2011) performed an automated classification of about 700 000 galaxies from the DR7 spectroscopic sample using an SVM algorithm, estimating the probability of a galaxy being in each of four morphological types: E, S0, Sab and Scd. All but one of the galaxies in our sample have an SVM classification.
Table 2. Galaxy Zoo classification.

| Class     | Number ERG | Fraction (per cent) | Fraction (per cent) | Notes |
|-----------|------------|---------------------|---------------------|-------|
| S edge-on| 267        | 65 ± 4              | 23 ± 1              | 1     |
| S other   | 21         | 5 ± 2               | 14 ± 1              | 1     |
| E         | 100        | 24 ± 2              | 60 ± 1              | 1     |
| Merger    | 13         | 3 ± 1               | 1 ± 1               | 1     |
| Don’t Know| 8          | 2 ± 1               | 1 ± 1               | 1     |
| $E_d$     | 101        | 25 ± 2              | 56 ± 1              | 2     |
| $S_d$     | 307        | 75 ± 4              | 44 ± 1              | 2     |

Notes: 1 – ‘raw’ votes; 2 – debiased votes.

Table 3. SVM classification.

| Class | Number ERG | Fraction (per cent) | Fraction (per cent) | Notes |
|-------|------------|---------------------|---------------------|-------|
| E     | 17         | 4 ± 1               | 21 ± 1              |       |
| S0    | 67         | 16 ± 1              | 28 ± 1              |       |
| Sab   | 331        | 79 ± 4              | 50 ± 1              |       |
| Scd   | 0          | 0                   | 0                   |       |

Ascribing again the most probable type to a galaxy, we obtain the fractions summarized in Table 3. We verify that a bit more than 3/4 of the ERG sample (79 ± 4 per cent) is constituted by spirals, with the remaining fraction containing mostly lenticular galaxies (16 ± 1 per cent) and ellipticals (4 ± 1 per cent). Unfortunately, in this classification there is not a distinction between edge-on and spirals with visible arms.

The SVM algorithm found 16 per cent of lenticular galaxies in our sample. There is a notorious difficulty for distinguishing lenticular galaxies from spirals or in images like those of SDSS. In our visual examination, non-edge-on galaxies without evidence of spiral arms were included in class 3. We verified that, considering only galaxies classified as S0 by the SVM method, half of them were classified by us as edge-on spirals and the other half was split more or less equally between ellipticals and spirals with visible arms.

4 THE DRIVER OF THE EXTREME RED COLOURS

The results of the Galaxy Zoo and SVM classifications presented in the previous section indicate that most of the galaxies in our ERG sample are spirals, in agreement with our visual classification. Actually, our results and the Galaxy Zoo classification show that the majority of our ERG sample is comprised of edge-on galaxies.

Between 2/3 and 3/4 of the galaxies above the RS are discs seen edge-on, as demonstrated by our visual classification (73 per cent) and by the Galaxy Zoo direct voting (65 per cent). What makes these galaxies so red? Effects of dust or of stellar populations? Indeed, galaxies may become redder either by increasing their extinction by dust or due to the presence of an intrinsically very red, old and/or high-metallicity population (see, e.g. the illustration of Bruzual & Charlot 2003 SSP spectra in fig. 1 of Cid Fernandes et al. 2005). This behaviour actually reflects the existence of an extinction–age–metallicity degeneracy.

To shed light on the nature of the extreme colours of ERGs, it is useful to know the morphological composition of galaxies pertaining to the RS.

For this exercise, we consider as members of the RS those galaxies between the two straight lines shown in Fig. 1. The upper line was used in Section 2 for defining the ERGs. The lower line is 0.2 bluer in $(g - r)$. There are 8635 objects of our sample in the RS, most of them with Galaxy Zoo and SVM classifications. The morphological mix of the RS sample is also shown in Tables 2 and 3, and is quite different from the ERG mix. For the RS, the classical early-type galaxies – E and S0 – dominate, the opposite of what is found for the ERG sample, which is dominated by spirals. But many spirals are also found in the RS, $\sim$40–50 per cent. Many of these red spirals might be examples of passive spirals as described by Masters et al. (2010b), but the RS also includes edge-on and dust-reddened spirals and, probably, spirals with large, red bulges. There are no late-type spirals (Scd) in the ERG and RS samples: they are in the blue cloud.

The clear differences in the morphological mix of the ERG and RS samples may be interpreted as evidence that extinction by dust, and not stellar population effects, is the main driver of the extreme colours of the objects in the ERG sample. The results in Tables 2 and 3 are consistent with the concept of the RS being populated by ‘dead galaxies’, those without significant star formation at least over the last 1–2 Gyr, irrespective of their morphological types. If the ERG extreme colours were due to intrinsically redder stars (due to extreme age or metallicity), we should expect that the dominant population would be comprised of ordinary early-type galaxies, not spirals as observed in our sample, since there is not any evidence that passive spiral galaxies harbour stellar populations which are intrinsically redder than those in ellipticals due to age or metallicity effects. Masters et al. (2010a) show that the typical $(g - r)$ reddening from face-on to edge-on spirals is about 0.15 mag. So, for a spiral galaxy to be in the ERG region of the CMD, it probably started in the RS, being a passive spiral. However, given the large variance in the reddening difference between face-on and edge-on spirals (see fig. 9 of Masters et al. 2010a), it is not impossible that even star-forming spirals may be members of the ERG sample if seen edge-on (see Tojeiro et al. 2013 for a discussion on ongoing star formation in red galaxies). Anyway, using the NED extinction calculator, one can verify that the variation in the extinction in $(g - r)$ for the Milky Way is larger than unit for Galactic latitudes lower than $\sim$5° from the Galactic plane.

We have also verified whether the nebular extinction, as measured by the flux ratio Hα/Hβ, is large in our ERG sample. The intrinsic (extinction-free) value of this ratio is insensitive to the physical conditions of the gas where the line emission is produced, ranging from 3.03 for a gas temperature of 5000 K to 2.74 at 20 000 K (Osterbrock 1989). We have used here the values of this ratio as measured by the STARLIGHT code (Cid Fernandes et al. 2005), which takes in to account the intrinsic line absorption (modelled with Bruzual & Charlot 2003 spectra). The distribution of Hα/Hβ for the 379 galaxies in the ERG sample with this ratio measured is presented in Fig. 4, and it is a clear indication that large extinctions are indeed present in this sample. Note that some objects (mostly early-types) may have very low line emission and, consequently, large errors in this line ratio. The median value for Hα/Hβ is 6.2, corresponding to $A_V = 2.1$ (assuming the Cardelli, Clayton & Mathis 1989 extinction law). For comparison, considering only RS galaxies, we obtain a median value for Hα/Hβ of 4.6, corresponding to $A_V = 1.3$. This exercise is also consistent with dust being the major driver of the colours of ERGs.

In this case, $A_V \approx 6.31 \log([\text{H}\alpha/\text{H}\beta]/2.86)$ (Stasińska et al. 2004).
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Figure 4. Distribution of the emission line intensity ratio Hα/Hβ for galaxies in the ERG sample. The dotted lines correspond to the interval expected for galaxies without intrinsic reddening.

Besides the differences in the morphological mix of the ERG and RS samples, there is also a clear difference in the fraction of edge-on objects: they are almost three times more frequent among ERGs than in the RS. To examine further this point, we present in Fig. 5 the distribution of the model minor to major axis ratio b/a of galaxy images in the r band for the ERG and RS samples. We adopt here ratios based on photometric fitting models, either exponential or de Vaucouleurs, ascribing to each galaxy the model with larger likelihood (see Alam & Ryden 2002 and the SDSS algorithms page for details), although the form of the distributions do not depend strongly of the model choice. The b/a distributions in Fig. 5 show that the ERG sample has a significantly large number of galaxies with low values of axial ratios (around b/a ~ 0.30) in comparison with the RS distribution, which presents a mostly flat distribution. These results are in good agreement with what was found by Alam & Ryden (2002) and are consistent with the predominance of edge-on galaxies in the ERG sample and less-flat, bulge-dominated galaxies in the RS sample (b/a ~ 0.75).

The prevalence of edge-on spirals (or low values for the axial ratios) in our sample of extreme objects seems a clear evidence that geometry is playing a significant role, as expected if the reddening is due to extinction by dust in galaxy discs.

Figure 5. Distribution of the model-type apparent axis ratio b/a of galaxy images in the r band (see text for details). Continuum line: ERG sample; dashed line: RS sample.

It is also worth mentioning that most not-edge-on spirals in the ERG sample also present prominent dust lanes. Some can be real passive spirals (Masters et al. 2010b), but not all, since some of them which seem strongly reddened in their centres, present blue discs indicative of ongoing star formation. Some ellipticals in our ERG sample also show significant dust lanes.

5 SUMMARY

In this work, we have selected a sample of ERGs, with colours redder than those found in the RS present in the CMD of galaxies. We have verified that most of the ERGs are edge-on spirals and that there are many more edge-on spirals in the ERG sample than among RS galaxies.

We propose that the reddest galaxies in our local universe have their extreme colours due mainly to the presence of dust. Many spiral galaxies seen edge-on in our sample may be passive and have an intrinsically red population, and extinction by dust places them above the RS. Additionally, even star-forming spirals seen edge-on may suffer enough extinction to be seen above the RS. On the other hand, it is unlikely that the extreme red colours of the ERG sample is produced by exceptionally old or high-metallicity red stars.

Reddening by dust seems to be a natural consequence of the prevalence of edge-on spirals in our sample of ERGs.

ACKNOWLEDGEMENTS

We are grateful to an anonymous referee whose comments led to a significant improvement in the presentation of our results. We also thank William Schoenel for his help with the STARLIGHT data used in this work. We thank the Brazilian agencies FAPESP and CNPq for supporting this work, which was part of the undergraduate project of ARS. We also wish to thank the team of the SDSS for their dedication to a project which has made this work possible.

Funding for the SDSS and SDSS-II has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Science Foundation, the US Department of Energy, the National Aeronautics and Space Administration, the Japanese
Monbukagakusho, the Max Planck Society and the Higher Education Funding Council for England. The SDSS website is http://www.sdss.org/.

The SDSS is managed by the Astrophysical Research Consortium (ARC) for the Participating Institutions. The Participating Institutions are the American Museum of Natural History, Astrophysical Institute Potsdam, University of Basel, University of Cambridge, Case Western Reserve University, The University of Chicago, Drexel University, Fermilab, the Institute for Advanced Study, the Japan Participation Group, The Johns Hopkins University, the Joint Institute for Nuclear Astrophysics, the Kavli Institute for Particle Astrophysics and Cosmology, the Korean Scientist Group, the Chinese Academy of Sciences (LAMOST), Los Alamos National Laboratory, the Max-Planck-Institute for Astronomy (MPIA), the Max-Planck-Institute for Astrophysics (MPA), New Mexico State University, Ohio State University, University of Pittsburgh, University of Portsmouth, Princeton University, the United States Naval Observatory and the University of Washington.

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