What determines the fraction of elliptical galaxies in clusters?

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\section*{ABSTRACT}
We study the correlation between the morphological mix of cluster galaxies and the assembly history of the parent cluster by taking advantage of two independently developed semi-analytic models for galaxy formation and evolution. In our models, both the number of cluster members and that of elliptical members increase as a function of cluster mass, in such a way that the resulting elliptical fractions are approximately independent of cluster mass. The population of cluster ellipticals exhibit a marked bimodal distribution as a function of galaxy stellar mass, with a dip at masses $\sim 10^{10} \, M_\odot$. In the framework of our models, this bimodality originates from the combination of a strongly decreasing number of galaxies with increasing stellar mass, and a correspondingly increasing probability of experiencing major mergers. We show that the correlation between the measured elliptical fraction and the assembly history of the parent cluster is weak, and that it becomes stronger in models that adopt longer galaxy merger times. We argue that this results from the combined effect of a decreasing bulge production due to a reduced number of mergers, and an increasing survival probability of pre-existing ellipticals, with the latter process being more important than the former.

\textbf{Key words:} galaxies: formation – galaxies: evolution – galaxies: bulges – galaxies: interactions – galaxies: clusters: general

\section*{1 INTRODUCTION}

It has long been known that early type galaxies (ellipticals and lenticulars) reside preferentially in dense regions of the Universe such as rich clusters, while late type galaxies represent a larger fraction of the galaxy population inhabiting regions of 'average' density. Such a morphology-density relation was noticed in early observational studies (indications of a correlation between the type of nebulae and the environment can be found in 'The Realm of Nebulae' by Hubble 1936), and was firmly established by Dressler (1980).

In the past decades, much observational information has been collected on the morphological distributions of cosmic galaxy populations, and on its dependence on the environment. Butcher & Oemler (1978a, 1984) showed, for the first time, that the fraction of blue (star forming) galaxies increases with increasing redshift. Detailed morphological studies have been carried out in the following years, demonstrating that the fraction of spiral galaxies increases with increasing redshift, and that this increase appears approximately balanced by a decrease in the fraction of the lenticular galaxies since $z \sim 0.5$. Over the same redshift range, the fraction of elliptical galaxies is approximately constant (Dressler et al. 1997; Fasano et al. 2000). In more recent years, detailed morphological studies have been pushed to lower mass ranges (Wilman et al. 2009), and to higher redshift, where the mean fraction of different morphological types does not appear to evolve significantly (Postman et al. 2003; Desai et al. 2007).

At a given redshift, clusters with similar mass (measured from either X-ray luminosity, or velocity dispersion) exhibit a non negligible scatter in their morphological composition (e.g. Poggianti et al. 2009). In the context of the currently accepted paradigm for structure formation (the $\Lambda$CDM model), it is logical to relate this cluster-to-cluster variance to the dynamical history of the cluster. Although difficult to test quantitatively, this expectation is confirmed by early observations that centrally concentrated clusters have typically large populations of ellipticals and lenticulars and relatively low numbers of spirals, while irregular, unrelaxed clusters are more spiral-rich and show weaker radial gradients in their morphological mix (e.g. Butcher & Oemler 1978b). In this paper, we will address this issue by considering two different semi-analytic models of galaxy formation,
and by relating the predicted fraction of elliptical galaxies to the accretion history of the simulated cluster haloes.

2 THE GALAXY FORMATION MODELS

In this paper, we take advantage of two independently developed galaxy formation models: the ‘Munich’ model, with the implementation discussed in [De Lucia & Blaizot (2007)] and applied to the Millennium Simulation, and the MORGANA model, as adapted to the WMAP3 cosmology in [Lo Faro et al. (2009)]. Hereafter, we will refer to the former model as DLB07. We note that in previous work, we have used the models presented in [Wang et al. (2008)] which correspond to the model by De Lucia & Blaizot (2007) used here, but has been adapted to a WMAP3 cosmology. In this paper, we use the model applied to the Millennium Simulation as this provides a larger volume and therefore a larger number of massive haloes.

The simulations employed in this study assume a different cosmology: the Millennium Simulation assumed a cosmological model that is consistent with WMAP first-year result. As shown in previous work, however, once the model is re-tuned to account for the change in cosmology, the basic results and trends do not change significantly [Wang et al. 2008]. In addition, we note that the two models adopt different definitions for the halo mass: in DLB07, this is given by $M_{200}$ and is computed from the simulation outputs as the mass contained in a sphere of radius $R_{200}$, for which the mean overdensity is 200 times the critical density of the Universe at the redshift of interest. For MORGANA, the masses are simply given by the sum of the particle mass associated with the halo, computed using PINOCCHIO [Monaco et al. 2002].

In this section, we provide a brief summary of the model elements that are relevant to the present study. We refer to the original papers for a more detailed discussion of the physical processes considered, and of the corresponding modelling adopted. Both models consider two different channels for the formation of bulges: galaxy-galaxy mergers and disk instabilities. The relative importance of these channels, in different environments and at different times, has been studied in detail in De Lucia et al. (2011), while in Fontanot et al. (2011) we focused on the statistics and properties of bulgeless galaxies. Both models used in this study assume a Chabrier Initial Mass Function.

Mergers are classified as minor or major according to their baryonic (gas + stars) mass ratio. If this is smaller than 0.3, the merger is classified as minor: the stellar mass of the secondary is added to the bulge component of the primary galaxy, and the merger is accompanied by a starburst. The resulting stars are added to the bulge component (in MORGANA) or to the disk component (in DLB07). If the baryonic mass ratio of the merging galaxies is larger than 0.3, we assume that we witness a major merger. In this case, both models assume that the disk components of the merging galaxies are completely destroyed. The remnant spheroidal galaxy can re-grow a new disk, if fed by an appreciable cooling flow. In previous work, we have found that the merger model adopted in MORGANA provides merging times that are systematically shorter (by up to an order of magnitude) than those adopted in the DLB07 model (see Section 7 of [De Lucia et al. 2010]). The shorter merger times adopted in MORGANA lead to a more efficient formation of bulges and to larger number densities of early type galaxies, particularly at high redshift. As we will show below, the different modelling adopted for galaxy mergers also affects the relation between the morphological fraction and the accretion history of dark matter haloes. In order to quantify the significance of this effect, in the following we will also show or discuss the results obtained from MORGANA using the same dynamical friction timescale prescription adopted by DLB07.

The treatment of disk instability differs significantly in the two models considered: both adopt the same stability criterion proposed in Efstathiou, Lake & Negroponte (1982) but use different definitions for the relevant physical quantities, and make different assumptions about the outcome of instabilities: DLB07 only transfer to the bulge a fraction of the stellar disc that is enough to restore stability. In the MORGANA model, half of the disk baryonic mass (both gas and stars) is transferred to the bulge. As discussed and shown in De Lucia et al. (2011), this translates into a more relevant contribution of disk instability to bulge formation.

In the framework of our models, most of the elliptical galaxies acquire their morphology through major mergers. Disk instability can contribute significantly for low and intermediate mass galaxies, depending on the adopted treatment for galaxy mergers and instabilities. As mentioned above, bulge dominated galaxies can later grow a new disc, if they are fed by an appreciable cooling flow. We have shown that the rates of disc regrowth are negligible for massive galaxies and at low redshift. They represent, however, a non-negligible component of the evolution of low and intermediate mass galaxies, particularly at high redshift (see Section 6 of De Lucia et al. 2011). As we focus on galaxy clusters, the model ellipticals considered in this paper are almost all satellite galaxies (with the exclusion of central cluster galaxies). For these galaxies, the bulge-to-total ratio is not affected after accretion onto a more massive halo in the MORGANA model. DLB07 accounts for mergers between satellites (that are, however, rare) so that the bulges of satellite galaxies can still grow through this physical mechanism. Finally, none of the models used in this study include ‘environmental’ processes such as tidal stripping or harassment, that can potentially affect the morphology of satellite galaxies orbiting in a massive cluster (e.g. Mastropietro et al. 2005).

In our previous work, we have considered alternative prescriptions to model bulge formation, including predictions obtained when the disk instability channel is switched off. We have verified that the results presented in the following do not depend significantly on these assumptions. Therefore, we will discuss only results obtained by our default models. As these data have not been used to ‘tune’ the models in the first place, they can be considered as genuine model predictions, and compared with available observational measurements.

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1 The most important difference between WMAP first and third year data is a lower value for the amplitude of matter fluctuations on $8\, h^{-1}$ Mpc scale ($\sigma_8$), which leads to a delay in structure formation (e.g. Wang et al. 2008).
The fraction of ellipticals in clusters

In this study we have considered galaxy clusters with masses in the range \(\log M/M_\odot = 14 - 14.8\), at redshift zero. In the simulation used by MORGANA, there are 100 clusters over this mass range. To compare the predictions from this model to those from DLB07, we have selected the same number of haloes from the Millennium Simulation, uniformly distributed in mass over the same mass range. In the following, we will define as ellipticals all galaxies that have a stellar bulge to total ratio larger than 0.9. When relevant, we will comment on how results can be affected by a different threshold.

Figure 1 shows the total number of galaxies (left panel), the number of ellipticals (middle panel), and the elliptical fractions (right panels) as a function of the cluster virial mass. Only galaxies residing within \(R_{200}\) have been considered in the DLB07 model. Since MORGANA does not provide information on the position of galaxies within dark matter haloes, we have simply considered in this case all galaxies associated with the final cluster. Given the different definitions adopted, any difference between model predictions (but we will see that these are very small) should be interpreted with caution. Filled and open symbols in Figure 1 correspond to galaxies more massive than \(10^9\) and \(10^{10}\) \(M_\odot\), respectively. The former limit corresponds to the approximate resolution limit of the Millennium Simulation, while the latter corresponds to a typical limit for observational studies.

Figure 1 shows that both the total number of galaxies and the number of ellipticals increase with increasing halo mass. When a lower stellar mass threshold is chosen, the predicted numbers are significantly higher. A cluster of mass \(2.5 \times 10^{14}\) \(M_\odot\) contains on average \(\sim 50\) (\(\sim 60\)) galaxies more massive than \(10^{10}\) \(M_\odot\) in the DLB07 (MORGANA) model. When considering a mass limit of \(10^9\) \(M_\odot\), the average number of cluster members within the virial radius increases to \(\sim 190\) (\(\sim 260\) in MORGANA). The number of ellipticals increases too, but not as much as the total number of galaxies. This is expected given that, as the stellar mass increases, a larger fraction of galaxies are classified as ellipticals (see Fig. 7 in [De Lucia et al. 2011]). Interestingly, the halo occupation distribution of the two models used in this study is different, with MORGANA always predicting a slightly larger number of cluster members with respect to DLB07. The difference is significant for the most massive clusters.
included in our sample, and when considering all galaxies more massive than $10^9 M_\odot$. We stress, however, that a different definition for cluster members has been adopted for the two models. In addition, we are using the dynamical information available from the simulations to define cluster members, while an accurate comparison with observational measurements should account for possible contamination by interlopers along the line of sight. As mentioned above, the merger times adopted in MORGANA are about one order of magnitude shorter than those adopted in DLB07. By using longer merger times in MORGANA, the number of cluster members increases even further.

The fraction of elliptical galaxies resulting from the numbers shown in the left and middle panel of Figure 1 does not vary significantly as a function of cluster mass, in agreement with observational measurements in the local Universe (Wilman et al. 2003; Poggianti et al. 2009). The predicted elliptical fractions are of the order of 10 per cent in both models, when all galaxies more massive than $10^9 M_\odot$ are considered. For a mass threshold of $10^9 M_\odot$, the expected fractions increase, and the scatter becomes larger. Interestingly, the halo to halo scatter appears to increase slightly with decreasing halo mass. This is more evident in the MORGANA model, but we note that in this case haloes are not distributed uniformly in mass and the number of clusters at the largest masses considered is quite low. Therefore, the very narrow range of elliptical fractions predicted by this model for the most massive haloes might be fortuitous, and just due to poor number statistics.

When considering all galaxies more massive than $10^{10} M_\odot$, the mean elliptical fraction is 0.22 for the DLB07 model, and 0.24 for MORGANA. This is lower than the average value of ~0.32 measured for the Wide-field Nearby Galaxy clusters Survey (WINGS), using a similar mass cut (Vulcani et al. 2011). We note, however, that only galaxies within 0.6 $R_{200}$ have been considered in this observational study, as this is the largest radius covered in all their cluster fields, and that the study is based on a definition of ellipticals that differs from that adopted in this paper (morphologies have been assigned using V-band images). In previous work (Simard et al. 2009), we have shown that the early-type fractions predicted by the DLB07 model compare well to observational measurements from the Sloan Digital Sky Survey (SDSS) in the local Universe and from the ESO Distant Cluster Survey (EDisCS) at redshift $z \sim 0.6$. Also in that study, however, a different (closer to that used in the observations) definition of ‘early-type’ galaxies was adopted, so that the predicted fractions shown in this study are not the same as those shown in Simard et al. In a forthcoming paper (Wilman et al., in preparation), we will carry out a more detailed comparison between the observed mix of different morphological classes and predictions from our galaxy formation models.

The left panels of Figure 2 show the predicted distributions of stellar masses for all galaxy clusters (thin histograms) and for the cluster ellipticals (thick histograms). These distributions have been obtained by stacking the galaxies in all clusters, and have been normalized to the total number of galaxies in each distribution. The two models provide very similar predictions, but those from MORGANA are more skewed towards less massive galaxies. Interestingly, both models predict a bimodal distribution for elliptical galaxies, with a pronounced ‘dip’ around $\sim 10^{10} M_\odot$. Unfortunately, this is below or approximately at the limit of the observational measurements for the WINGS sample used in Vulcani et al. (2011). We note that this bimodal behaviour is found in our models also when considering the global elliptical population (i.e. not only ellipticals in clusters), which does not appear to be supported by available observations (e.g. Trentham & Hodgkin 2003, Driver et al. 2003). We stress that our models (like most of the recently published models) overpredict the number densities of small to intermediate mass galaxies (Fontanot et al. 2009), so the importance of the peak at small masses is likely over-estimated.

In both models, the bimodal distribution of the cluster elliptical masses is significantly reduced (but still apparent in the MORGANA model) when the adopted threshold for defining a bulge dominated galaxy as an elliptical is lowered to $z \sim 0.7$. In this case, only one peak is visible in the DLB07 predictions at masses $\log (M_{\text{bulge}}) \sim 10.5$. We have verified that, in our model, this bimodality is not significantly affected when the disk instability channel for bulge formation is switched off, so a differential efficiency of bulge formation through disk instability is not responsible for the shape of the cluster elliptical mass distribution shown in Figure 2. In our previous work (De Lucia et al. 2011), we have shown that disk regrowth is more efficient for intermediate mass galaxies. In order to test if this could be responsible for the observed dip at intermediate masses, we have calculated the mass distribution of all galaxies that have been ellipticals in their past, either considering only those surviving at redshift zero (i.e. excluding those that have merged with other galaxies) or all galaxies in the merger trees of the cluster ellipticals. In both cases, we find that the predicted mass distribution exhibit a marked bimodality, with a pronounced ‘deficit’ of elliptical galaxies at intermediate masses.

We interpret this bimodality as a result of the increasing probability of suffering a major merger with increasing mass (see Figure 9 in De Lucia et al. 2009 and Figure 6 in Wang & Kauffmann 2008), and of the strongly decreasing number of galaxies of larger masses (as shown by the thin lines in Figure 2). The convolution of these distribution functions results in a lower number of intermediate mass galaxies suffering of major merger events in their past history, compared to galaxies residing in the low and high mass peaks of the distributions shown in the left panels of Figure 2. In particular, Figure 3 of Wang & Kauffmann (2008) shows that the region where the dip in the mass distribution of elliptical galaxies is visible, corresponds to a regime where the probability of suffering of a minor merger is significantly larger than that of experiencing a major merger. This happens because, during the time that elapses between a halo merger and the actual merger between the galaxies residing at the centre of the merging haloes, the stellar mass of the satellite does not increase significantly, while the central galaxy grows in mass as it is fed by cooling from the surrounding hot halo. As a consequence, the stellar mass ratio between the two galaxies decreases, so that a major merger between two haloes can lead to a minor merger be-
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Figure 2. Distribution present day stellar masses (left panel) for model ellipticals in our cluster sample, and for their parent halo mass at the time of accretion (right panels). The distributions shown have been obtained by stacking all clusters in the sample, and normalizing to the total number in each distribution. Solid and dashed lines refer to the cases when all galaxies more massive than $10^9$ and $10^{10}$ $M_\odot$ are considered, respectively. Thin and thick lines (black and red in the online edition of the Journal) are for all galaxies and for those that are classified as ellipticals, respectively.

Figure 3 in Wang & Kauffmann (2008) shows that the probability of experiencing a minor merger is largest at intermediate masses, which explains why lowering the adopted bulge-to-total threshold fills the intermediate region, and tends to wash out the bimodality.

For each cluster member in our sample, we have traced back their main progenitor until the galaxy is for the last time a central galaxy of a dark matter halo, and we have recorded the parent halo mass at this time. In the following, we refer to this as the ‘time of accretion’, although this will not always coincide with the time when the galaxy is accreted onto the main progenitor of the final cluster (De Lucia et al., in preparation). The right panels of Figure 2 show the distributions of halo masses at accretion for all cluster members (thin lines) and for the ellipticals (thick lines). Again, the distributions obtained for all clusters have been stacked and normalized to the total number of galaxies in each of them.

The figure shows that, in both models, elliptical galaxies tend to be accreted when they reside in more massive haloes with respect to the total population of cluster members (the distribution predicted by MORGANA has a higher lower mass limit than in the DLB07 model: i.e. in MORGANA, ellipticals tend to be accreted, on average, in more massive haloes than in the DLB07 model). This is not surprising considering that ellipticals represent a larger fraction of the most massive galaxies, and that there is a relatively tight correlation between the galaxy mass and that of the parent halo mass for central galaxies (e.g. Wang et al. 2006).

4 THE ASSEMBLY OF CLUSTERS WITH DIFFERENT ELLIPTICAL FRACTIONS

In the previous section, we have shown that ellipticals tend to be accreted in larger haloes, with respect to the entire
cluster galaxy population. Given these results, one would expect naively that haloes that have acquired a larger fraction of their mass through the accretion of ‘massive’ haloes would host a larger fraction of ellipticals. One has to consider, however, that elliptical galaxies can also disappear from the sample of cluster members by merging with the central galaxies of the hosting halo (or with other satellites in the DLB07 model).

In order to address this issue, we have analysed the accretion histories of all clusters included in our sample. For each halo, we have traced back in time its main branch, i.e. the branch of the tree that is obtained by connecting the halo to its main progenitor. We have then considered all substructures residing in the main branch at each time, and have traced each of them back in time until they were main haloes of a FOF-group. The top panels of Figure 3 show the mass distributions of accreted haloes for the clusters that host an elliptical fraction lower (thin dashed lines) than the 10th percentile, and higher (thick solid lines) than the 90th percentile of the distribution of elliptical fractions measured for all 100 haloes considered. Again, the distributions from the two cluster samples have been stacked. Different columns correspond to different models, as indicated by the legend, while the bottom panels show the corresponding cumulative distributions. The differential distributions shown in the top panels of Fig. 3 have been weighted by mass in order to remove the dominant mass dependency and emphasize the differences between the two samples.

In the DLB07 model (left panels), there is a clear difference between the two samples, which is more evident when looking at the cumulative distributions: clusters that host the highest elliptical fractions also accreted a larger number of haloes more massive than \( \sim 10^{11} \, M_\odot \), with respect to the clusters that host the lowest elliptical fractions. Interestingly, the difference between the two samples persist over the entire mass range: this implies a lower contribution from diffuse accretion for clusters with large elliptical fractions. In the standard MORGANA model, no significant difference is found between the two samples. If, however, longer merger times are adopted (right panels), then a difference between the haloes with largest and lowest elliptical fractions becomes visible, and it is of the same order of magnitude of that found in the DLB07 model. At first sight, this result appears counter-intuitive because one would expect that shorter merger times would translate into a better matching between the morphological mix of the galaxy population and the assembly history of the halo. One has to consider, however, that changing the merger times would affect the elliptical galaxy population in two distinct ways: on the one hand, longer merger times would tend to decrease the number of mergers (and therefore the number of bulge dominated galaxies). On the other hand, longer merger times would also tend to ‘preserve’ the pre-existing ellipticals from being accreted onto the central galaxies (or from merging with other satellites if this physical process is included). When adopting longer merger times in MORGANA, we find that the second process would be slightly more important than the first. As a consequence, both the total number of cluster members and the number of elliptical members would increase. This implies that longer merger times preserve a better memory of the accretion history of the parent dark matter haloes, thereby creating a stronger correlation between the morphological mix of the cluster galaxy population and its dynamical status.

5 DISCUSSION AND CONCLUSIONS

At fixed cluster mass, the observed properties of the cluster galaxy population exhibit a large variation. Such a scatter is in part due to observational uncertainties in the observed quantities. In the hierarchical framework, however, it is natural to link the observed halo-to-halo scatter to a range of dynamical histories of the parent cluster. In this paper, we have investigated the link between the predicted fraction of elliptical galaxies and the accretion history of the parent dark matter halo, by taking advantage of two different semi-analytic models of galaxy formation. Our main results can be summarized as follows:

- For both models used in our study, the predicted elliptical fractions do not vary significantly as a function of the cluster mass, for the range of masses considered (\( M_{200} \gtrsim 10^{14} \, M_\odot \)). This appears to be in qualitative agreement with observational measurements (Wilman et al. 2004; Poggianti et al. 2003; Simard et al. 2000). In our models, a constant elliptical fraction results from an increasing number of both cluster members and elliptical members, as a function of cluster mass.
- Cluster ellipticals exhibit a marked bimodal distribution in stellar mass. In both models, the bimodality is reduced when a lower (\( \sim 0.7 \) bulge-to-total threshold is adopted for selecting elliptical galaxies. The distribution of stellar masses for elliptical galaxies preserves its bimodal behaviour when considering all galaxies (i.e. is not limited to cluster ellipticals).
- Since ellipticals are the dominant population among massive cluster members, one finds that these galaxies have been accreted, on average, onto the cluster when residing in relatively massive structures (more massive than those of the overall cluster galaxy population). This creates a correlation between the observed fraction of ellipticals and the accretion history of the halo that is, however, not strong.

In the framework of our models, the bimodal distribution of elliptical stellar masses is not due to a more prominent role played by disk instability and/or disk regrowth for intermediate mass galaxies (De Lucia et al. 2011). We argue that this bimodality results simply from the convolution between the strongly decreasing number of galaxies and the increasing probability of experiencing a major merger event in the past, for increasing galaxy mass (De Lucia et al. 2004; Wang & Kauffmann 2008). For galaxies with mass \( \sim 10^{9} \, M_\odot \), the probability of having experienced a major merger is not large, but there are many low-mass galaxies. On the other hand, almost all galaxies with mass \( \gtrsim 10^{11} \, M_\odot \)
The fraction of ellipticals in clusters

Figure 3. Mass distribution of haloes accreted on the main branch of each cluster in our sample. Thin dashed lines (blue in the online edition of the Journal) are for haloes with an elliptical fraction that is lower than the 10th percentile of the distribution, while thick solid lines (red in the online edition of the Journal) correspond to the haloes whose elliptical fraction is larger than the 90th percentile of the distribution. The differential distributions in the top panels have been weighted by mass, in order to remove the dominant mass dependence and emphasize the differences between the two samples.

have experienced at least one major merger during their lifetime so, although the number of massive galaxies is low, this mass bin is dominated by elliptical galaxies.

We argue that clusters that host larger fraction of ellipticals have a lower contribution from diffuse accretion than clusters with lower elliptical fractions (i.e. they accrete more haloes, over the entire mass range probed by our simulations). In addition, we find that the correlation between the observed fraction of elliptical galaxies and the accretion history of the halo can be weakened in the case of short merger times. This would reduce the number of elliptical cluster members by having them accreted onto the central cluster galaxies or merged with other cluster members. In this framework, elliptical satellites have been formed before their accretion onto the cluster. The measured fraction of ellipticals is determined by the balance between the disappearance of ellipticals due to accretion and mergers, and the recent accretion of relatively massive structures (that would likely host an elliptical central galaxy). A better ‘memory’ of the accretion history is preserved when merger times are longer. In this case, a stronger correlation between the morphological mix of cluster populations and the dynamical status of the cluster is expected.

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This paper is dedicated to my grandmother.
This paper has been typeset from a \TeX/\LaTeX file prepared by the author.

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