NATIONAL CENTRE FOR NUCLEAR RESEARCH

Abstract

Identification and characterization of strong gravitational lenses and low surface brightness galaxies using deep learning

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Despite the success of the ΛCDM model over the past two decades, the model has encountered several unresolved tensions with observations. These include the nature of dark energy and dark matter, the missing baryon problem, and galaxy-scale tensions, collectively known as small-scale problems. To resolve these tensions, we need to test the predictions of the ΛCDM model on galaxy systems, which could challenge and refine our understanding of the Universe. Strong gravitational lenses (SGLs) and low surface brightness galaxies (LSBGs) are two such sources that we could use to resolve the tension of the ΛCDM model with observations. SGLs are systems formed when the gravitational field of a massive foreground galaxy distorts the image of a background galaxy or quasar to produce multiple images, arcs, or rings of the background source. SGLs can be used to constrain the cosmological models and estimate cosmological parameters. LSBGs are generally defined as galaxies that are fainter than the night sky, making them difficult to detect. Current predictions estimate that LSBGs occupy a significant fraction of the total galaxy population. Upcoming large-scale surveys, such as the Legacy Survey of Space and Time (LSST) and Euclid, are expected to identify about 10^5 SGLs and more than 10^5 LSBGs in the coming years, paving the way for the big data era in astronomy. However, the identification of these systems is challenging due to the rarity of SGL systems and the difficulty of distinguishing LSBGs from artefacts. In this thesis, inspired by the success of deep learning models in analysing everyday images, I introduce transformer models for identifying SGLs and LSBGs from large-scale surveys and successfully implement these models for this purpose.

To compare the performance of the transformers with CNNs for the identification of SGLs, I constructed and trained 21 transformer models and five CNNs to identify gravitational lenses from the simulated dataset of the Bologna lens challenge. I used four different metrics for evaluation: classification accuracy, the area under the receiver operating characteristic (AUROC) curve, and TPR0 and TPR10 scores (two metrics of evaluation for the Bologna challenge). I compared the performance of the transformer models and the best-performing models from the Bologna lens challenge and found that the transformer models performed better than all the models that participated in the challenge, including the CNNs that won the challenge. Transformer models can identify SGL candidates with a high level of confidence and will be able to filter out potential candidates from real data. I tested the transformer models on the SGL candidates found by the SGL searches in the Kilo Degree Survey (KiDS) and despite not being trained on the KiDS data, the transformer models were able to identify 65% of the SGL candidates.

In my next work, I study the use of transformer models in separating LSBGs from artefacts in the data from the Dark Energy Survey (DES) Data Release 1. I created eight different transformer models which achieved an accuracy of $\sim 94\%$ and used two ensembles of these eight models to identify LSBGs from DES. Using the transformer models, I then searched for new LSBGs from the DES that the previous searches may have missed and found 4 083 new LSBGs that had not been reported in the previous searches. Subsequently, the properties of the newly found LSBGs are investigated, along with an analysis

of the properties of the total LSBG sample in DES. With the addition of 4 083 new LSBGs I increased the sample size of known LSBGs in DES by $\sim$ 17% and increased the number density of LSBGs in DES to 5.5 deg^{-2}. The new LSBG sample consists of mainly blue and compact galaxies. I performed a clustering analysis of the LSBGs in DES using an angular two-point auto-correlation function and found that LSBGs cluster more strongly than their high-surface-brightness counterparts. This effect is mainly driven by the red LSBG. I associated 1310 LSBGs with galaxy clusters and identified 317 ultra-diffuse galaxy candidates among them. Analysing the cluster-centric properties, I found that these cluster LSBGs in DES are getting bluer and larger in size towards the edge of the clusters when compared with those in the centre.

For my next work, I studied the scope of transfer learning for the identification of LSBGs. I trained two ensembles of transformer models with data from the DES which achieved an accuracy $\sim$ 95%. Subsequently, these models are tested on the data of the Abell 194 cluster acquired from targeted observations with the Hyper Suprime-Cam (HSC), which is two orders of magnitude deeper than the DES data. I identified a sample of 171 LSBGs, of which 87 are completely new from the HSC data and further classified 28 LSBGs as ultra-diffuse galaxies (UDGs). The number of UDGs in the Abell 194 cluster aligns with observations in the literature that the number of UDGs scales proportionally with the mass of the cluster. Analyzing the cluster-centric properties of the sample, I found that the LSBGs and UDGs near the cluster centre are brighter and have higher Sérsic index values compared to those in the outer regions. Additionally, the LSBGs near the cluster centre tend to be redder than those in the outer parts of the Abell 194 cluster, with this trend being more pronounced in $FUV - NUV$ and $NUV - r$ colors compared to the $g - r$ color. Examining the color-magnitude ($NUV - r$ vs M_r) space of LSBGs it is found that the majority of the NUV emitting LSBGs are in the blue cloud with only two LSBGs being red in color which both are massive galaxies.

I have shown that the transformer models have the potential to be on par with CNNs as state-of-the-art algorithms in identifying SGLs and LSBGs. In addition, I have shown that transfer learning from a shallow survey to a deeper survey using transformer models could be successfully achieved. The methodology, I have developed as part of this thesis could prove valuable for identifying and analyzing astronomical data in upcoming surveys like LSST and Euclid.