A *NuSTAR* VIEW OF THE PRE-MERGING GALAXY CLUSTERS A399 & A401: COMBINING 2D LENSING MASS MAPS, SUNYAEV ZEL'DOVICH, AND X-RAY DATA TO SEARCH FOR HINTS OF NON-THERMAL EMISSION

1 Introduction

Galaxy clusters form at the nodes of dark matter filamentary structure due to the collapse of peaks in the primordial density field, and are powerful probes of astrophysics and cosmology; this makes them priority targets for current and upcoming large scale surveys. Clusters are complex systems, with many components and physical processes. The combination of multiple wavelengths places better constraints on fundamental properties (like mass) than assessing wavelengths independently. We have very deep optical/near-infrared observations of a large set of clusters, producing an unprecedented set of **individual** 2D weak-lensing mass maps; such mass maps are very rare, and are a **unique** scientific resource.

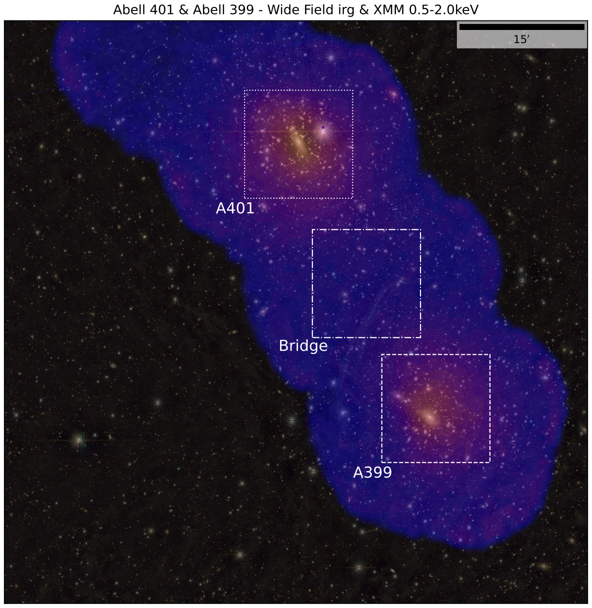

Figure 1: Optical+X-ray image of Abell 401 and Abell 399, the targets of this proposal. Archival *XMM* data have been smoothed and overlaid on the optical data; blue colours represent low count-rates, yellow colours represent high count-rates.

Our survey relates to all aspects of galaxy cluster science, but the core aims are to explore the scatter of individual galaxy clusters from scaling relations, particularly those used to predict mass of clusters (data quality is not high enough for direct mass measurement in most cases). Such deviations must be quantified to use clusters for cosmology; particularly relevant for the Dark Energy Survey (DES) and the upcoming Legacy Survey of Space and Time (LSST). A major source of scatter in scaling relations are clusters that are disturbed/unrelaxed, a state induced by merger activity. Mergers inject large amounts of energy into the intra-cluster medium (ICM), with effects that range from shock heating of the ICM to the re-acceleration of electrons (also known as cosmic rays [3]). Cosmic rays, in concert with the magnetic fields of clusters, produce radio emission; a signature of merger activity. Both magnetic fields and cosmic rays are a source of 'non-thermal pressure support' in the ICM, which is known to lead to hydrostatic bias; a difference between masses measured through the astrophysics of the ICM and those that directly probe the total halo mass (weak-lensing) [5]. Non-thermal processes in the ICM are difficult to study, with most insight coming from radio observations. Hard X-ray emission from Inverse-Compton (IC) scattering of Cosmic Microwave Background (CMB) photons provides another probe of these processes; we hope to use *NuSTAR* data in concert with our mass maps, existing X-ray data, and Sunyaev Zel'Dovich (SZ) observations to develop techniques and models to put constraints on non-thermal processes.

There have been several searches for non-thermal X-ray emission from massive galaxy clusters [11, 10, 16, 13, 7], but an unambiguous detection has been elusive, though constraints have been placed on the non-thermal X-ray flux. As such, the search for IC emission is worthwhile even ignoring our other scientific goals. The presence of cosmic rays and magnetic fields in clusters is not in doubt (the radio emission detected in many clusters confirms this), so we **must** expect that an IC signal is present. We choose to focus on a pair of massive interacting clusters which are a part of our survey, Abell 399 and Abell 401 (see Figure 1 for an optical & smoothed *XMM* image of the system).

These galaxy clusters are known to be interacting, with a bridge of gas detected between them via Planck, ACT, and MUSTANG-2 SZ observations [6], and subsequent deep LOFAR studies of radio emission [2, 4, 9]. Some of this work placed constraints on the magnetic field present within the bridge, finding emission consistent with a second order Fermi model of electron re-acceleration. There have also been low-energy X-ray (comparative to *NuSTAR*) studies of the clusters, and the bridge between them. *Suzaku* observations determined the presence of a shock (a temperature break was measured) between the two clusters [1], and an *XMM* study found that the clusters are likely pre-merger [12].

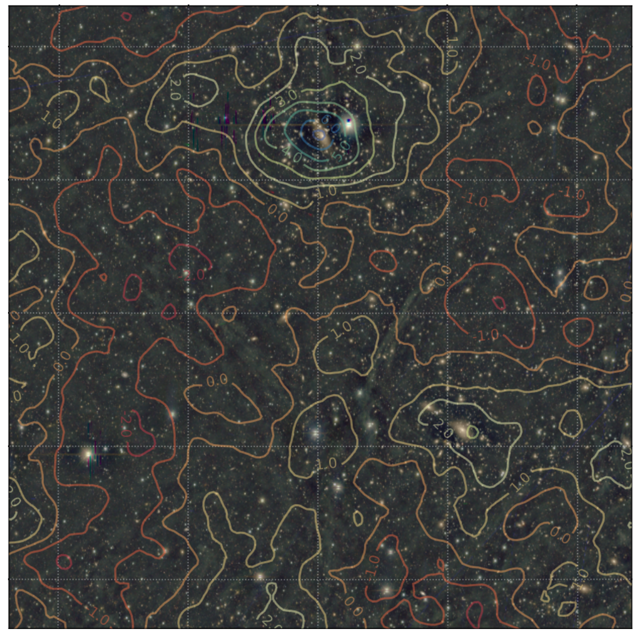

Figure 2: A 2D weak-lensing mass map of A401 and A399, indicated by contours generated from the aperture mass signal-to-noise.

Our as yet unpublished 2D weak-lensing mass map of these clusters (see Figure 2) does not show much of a trace of the bridge between these systems, but confirms A401 is more massive than A399. We find a clear bridge of red-sequence galaxies between A401 and A399. The galaxy distribution outside the bridge is clearly bi-modal. It is also well established that A401 and A399 both have radio halos [8]; given the early stage of their merger, these are likely a result of the earlier merger histories of the clusters. All of this makes them a very interesting target for *NuSTAR* observation.

The possible benefits of this study are far reaching, as taking steps towards the empirical quantification of non-thermal pressure support in clusters will **(a)** further the core aims of our survey (quantifying deviations of individual clusters away from expected behaviours); **(b)** improve measurements of hydrostatic mass (providing a competitive independent mass calibration for large-scale optical surveys); **(c)** improve H_0 measurements cluster from pressure profiles [15] by accounting for hydrostatic bias; and **(d)** help quantify the differences between disturbed and relaxed systems.

2 Scientific Justification

NuSTAR is the only telescope that can fulfill these scientific goals, as it is unique in its ability to focus high energy X-rays. *INTEGRAL* and *Swift* can probe similar energy ranges, but their coded-mask instruments cannot unambiguously assign hard X-rays to a galaxy cluster.

Complex interacting systems such as A401-A399 often deviate from scaling relations - they are subject to powerful astrophysical processes which can effect velocity of the ICM, and change the entropy of the gas. The interaction between these two clusters is not advanced, but the evidence

Table 1: Properties of the targets, ordered by descending priority. Column **(1)**: Name of the component of the A401-A399 system; **(2)**: Central Position RA; **(3)**: Central Position Dec; **(4)**: *XMM*-measured temperature within 1000 kpc (or 500 kpc for the bridge); **(5)**: *XMM*-derived flux within 0.5-10.0 keV **(6)**: Predicted *background subtracted* count-rate from WebPIMMS, for both modules (FPMA+FPMB) for a 50% PSF extraction, within 3-79 keV; **(7)**: Within 3-10 keV; **(8)**: Within 10-20 keV; **(9)**: requested exposure time [ks].

Name	RA [deg]	Dec [deg]	*XMM*-T_X [keV]	F_X [$10^{-13}\frac{\text{ergs}}{\text{cm}^2\text{s}}$]	3-79 cps [$10^{-3}\frac{\text{ct}}{\text{s}}$]	3-10 cps [$10^{-3}\frac{\text{ct}}{\text{s}}$]	10-20 cps [$10^{-3}\frac{\text{ct}}{\text{s}}$]	t_{exp} [ks]
A399	44.458	13.049	$6.35^{+0.12}_{-0.12}$	437	66.910	60.13	6.826	100
Bridge	44.560	13.300	$6.45^{+1.60}_{-1.15}$	8.35	8.175	10.117	0.72	300
A401	44.740	13.579	$7.14^{+0.09}_{-0.09}$	784	135.3285	117.2607	17.2704	80

of their interaction has already been detected across various wavelengths; our proposed *NuSTAR* observations are a chance to see whether evidence exists in hard X-rays as well. We believe this would be the first time *NuSTAR* would observe a pre-merger cluster pair, and bridge. Hard X-ray emission will combine with our mass maps, and the other existing data, to help build the most complete models of this cluster pair. We will use *NuSTAR* data to place a constraint on the magnetic field using *NuSTAR* data as we search for IC emission; this will provide an independent comparison to the value measured by through radio observations [2] - given the rarity of magnetic field strength measurements in clusters this should be very valuable. The ICM of both galaxy clusters is high temperature, and previous work has found temperature enhancement along the direction of the bridge, likely a result of shocking from the merger. *NuSTAR*'s large energy range will help to search for regions of significant temperature enhancement, and to confirm existing measurements.

3 Observing Plan

We are requesting observations of the three main components of this system, Abell 399, Abell 401, and the bridge between them. The requested observations are illustrated in Figure 1 by the white boxes that indicate the size of the *NuSTAR* field of view. Data reduction will be performed using standard NuSTARDAS tools, assembling event lists and good-time intervals through the use of `nupipeline`. We will also validate the automatically generated good-time-intervals by manually inspecting light-curves created from the uncleaned event lists. If the automatic good-time-intervals are overzealous, then we will manually adjust them.

Data analysis of these observations will be multi-faceted, as we have multiple scientific goals. Initially we will use *NuSTAR* and *XMM* data independently to examine the temperature structure of the clusters. We will check for any extreme temperature enhancement not evident in *XMM* data. We note a known difference of ~10-16% between *NuSTAR* and *Chandra* temperature constraints [14], and consider that we may have to perform a similar analysis and compare *XMM* and *NuSTAR* temperature constraints for a sample of clusters. The `nuskybgd` tool will be used for background analysis, following the example of [10], and PSF effects on effective area at different energies accounted for by using the `nucrossarf` tool, following the method of [13]. We will then perform a search for IC emission in a similar manner to previous work [10, 11, 16]. We will also add to the existing methodology by attempting to constrain the thermal structure of the clusters with existing *XMM* data, if (as we expect) it provides better constraints on temperature - this would give model fits for an IC component to *NuSTAR* high-energy data more constraining power. We will then move on to our multi-wavelength analysis, which will make use of our 2D weak lensing mass maps, SZ observations, existing X-ray observations, and a forward modelling approach using a theoretical framework of the ICM, to model the thermal X-ray output of the galaxy cluster; we will apply *NuSTAR* instrumental characteristics and compare the modelled version with our observation - an excess emission in the hard X-ray band could be a detection of non-thermal processes. Finally, we aim to apply this approach to every applicable cluster, which will involve a uniform re-analysis of clusters in our survey that have 2D weak-lensing mass maps and *NuSTAR* data (of order 10). All our analysis techniques will be made open-source and available to the community.

4 Feasibility

The requested observations, with our predictions of the expected count-rates in different energy bands, are presented in Table 1. Predicted count-rates are calculated using *XMM* constraints on target properties (measured for our survey) and using WebPIMMS to simulate the emission we can expect to detect with *NuSTAR*. All count-rates account for the *NuSTAR* background.. It is possible the high-energy (above ~10 keV) count-rate may be higher in reality than we predict, if there is appreciable non-thermal emission, as we have performed these prediction assuming only an absorbed APEC plasma emission model. We assume the same hydrogen column density (0.99×10^{22} cm^2), and redshift (z = 0.072) for all simulations.

We have requested a significantly longer exposure time for the bridge than for the two galaxy clusters, because the X-ray flux is so much lower; the requested exposure times should help us to achieve a minimum of 200 10-20 keV counts above background in bridge observation, and substantially more in the galaxy cluster observations; there will also be sufficient lower energy (3-10 keV) to spatially resolve the temperature structure of the two clusters. The more massive cluster of the system, Abell 401, has already been selected for a *NuSTAR* observation (though it has not been performed); unfortunately however the requested exposure time (per the NUMASTER HEASArc table) is only 20 ks, which is not sufficient for our scientific goals.

We have also made use of the *NuSTAR* target visibility checker, and determined that there are no stray light issues that would complicate observations. The tool reports that there are moon aspect angle violations and spacecraft star tracker violations at various points during cycle 10, but that they all last approximately 2 days; this should not significantly impact scheduling the observations. More restrictive are the solar aspect angle violations, which apply from 2024-06-01 through 2024-06-19, and 2025-03-23 through 2025-05-31. While not insignificant time periods, it should be possible to schedule around them.

5 Conclusion

We hope to expand the knowledge of hard X-ray emission from clusters by searching for evidence of inverse-Compton emission from the interacting galaxy clusters A401 and A399; and in doing so probe cluster magnetic fields and non-thermal processes. We will use *NuSTAR* observations to help develop forward modelling of a theoretical framework which will be simultaneously applied to very high-quality 2D weak lensing mass maps, Sunyaev Zel'dovich observations, and existing X-ray observations; this is in order to search for non-thermal emission, by looking for differences. This framework will be applied more widely to other clusters in our surve once developed, and will also be a resource for the wider cluster astrophysics and cosmology community.

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