Constraining the Dark Matter Self-Interaction Cross-Section with Numerical Simulations of 1E 0657-56

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ABSTRACT

We present results for constraining the self-interaction cross-section of dark matter by comparing X-ray and weak-lensing observations of the galaxy cluster 1E 0657-56 (the so-called “bullet cluster”) with results from N-body/hydrodynamical simulations. This cluster shows a high-velocity merger in the plane of the sky with a prominent bow shock that gives a subcluster velocity of roughly 4500 km s^{-1}. A comparison of the X-ray image and weak-lensing mass map shows that the subcluster gas core lags the dark matter clump, which is coincident with the subcluster galaxies, indicating that the dark matter is not fluid-like. These observations allow for three independent methods for estimating the self-interaction cross-section of dark matter. Analytic estimates based on these methods have previously been determined. This work seeks to put tighter constraints on these results using N-body/hydrodynamical simulations that include the effects of self-interacting dark matter. We show that the analytic estimates are improved upon, and that further improvements will be made when the simulations are compared with upcoming results from new observational data.

INTRODUCTION

E1 0657-56 provides a rare opportunity for constraining the self-interaction cross-section of dark matter. It is one of the hottest and most X-ray luminous galaxy clusters known and it has a high velocity (roughly 4500 km s^{-1}) merger occurring in the plane of the sky (Markevitch et al. 2004, hereafter M04). Figure 1 shows the X-ray image of this cluster with the weak-lensing mass contours overlaid (derived by Clowe et al. 2004). The gas bullet lags behind the subcluster dark matter clump, indicating that the dark matter is not fluid-like. Also visible is a cooler North-South X-ray bar, which is most likely an edge-on pancake-like remnant of the main cluster's gas core and gas stripped from the subcluster's outer atmosphere (M04). The ideal geometry of the merger and the high-quality data available allow for tight constraints to be placed on the self-interaction cross-section of dark matter using three independent methods. These methods are outlined below.

COLLISIONAL CROSS-SECTION ESTIMATES

Three independent methods for estimating the collisional cross-section, , are given below, along with results given by analytic calculations. The calculations assume a King profile for the mass in each cluster and that the subcluster has passed once through the core of the main cluster. For a deeper discussion of these methods and results, see M04.

- ♦ *Gas- dark matter offset:* As can be seen in Figure 1, there is a ~23" offset between the subcluster's gas core and dark matter centroid. This indicates that the scattering depth of the dark matter subcluster cannot be much greater than 1, otherwise it would experience stripping and drag deceleration similar to the gas core and there would be no offset. Simple analytic calculations give $/m < 5$ cm^2 g^{-1}.
- ♦ *High subcluster velocity:* The observed velocity of the subcluster is in good agreement with the expected free-fall velocity onto the main cluster, suggesting that the subcluster could not have lost much of its momentum to drag forces originating from dark matter collisions. An analytic estimate gives $/m < 7$ cm^2 g^{-1}.
- ♦ *Survival of dark matter subcluster:* The mass-to-light ratio of the subcluster is in good agreement with that of the main cluster and with the universal cluster value, indicating that the subcluster has not lost a large fraction of its dark matter due to collisions (which would result in a lower M/L ratio for the subcluster). Analytic results give $/m < 1$ cm^2 g^{-1}.

THE ROLE OF SIMULATIONS

In order compare more directly to the observations, and to do away with the simplifying assumptions made for the analytic calculations, detailed N-body/hydrodynamical simulations of the merger are needed. To this end, we have modified the publicly available SPH code GADGET2 (Springel et al. 2005) to include collisional dark matter as a new particle type. The code employs a Monte Carlo technique with isotropic scattering to model the dark matter self-interaction (this method has previously been used by Burkert 2000 and Yoshida et al. 2000). Results from a 10^6 particle bullet cluster simulation with this code are shown in Figure 2. The subcluster dark matter and galaxy centroids are indicated by the blue and red circles respectively. Intensity indicates total mass column density. For each cluster dark matter, galaxy, and central cD galaxy components were included. Initial conditions were chosen such that at the observed separation of 660 kpc the projected mass profile of each cluster matches the results from the lensing mass map to within 10%, which is well within the observational errors. King models were chosen for each cluster as they reasonably reproduce the observations and are expected to give conservative estimates on the effects of self-intereacting dark matter since the central densities (and therefore the column density “seen” by the bullet cluster) are relatively small. The dark matter lags the galaxies since it loses momentum due to collisions with with the main cluster halo particles. For this simulaiton we set $/m \sim 1$ cm^2 g^{-1}, which gave a subcluster dark matter/galaxy offset of 34 kpc (~8”).

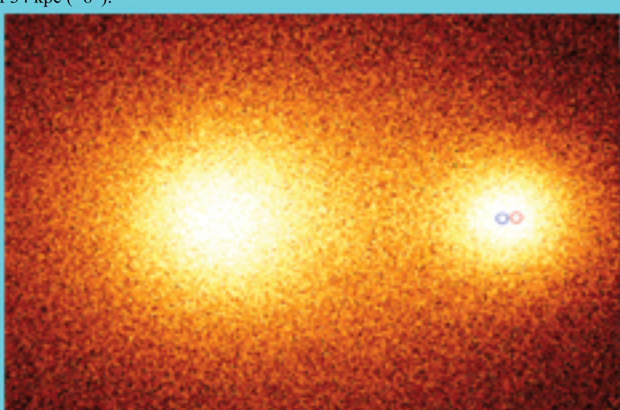

Figure 2: Simulation snapshot from head-on run with $\sigma/m \sim 1$ cm^2 g^{-1} (intensity indicates total surface mass density). The blue circle marks the centroid of the subcluster DM halo while the red circle marks the subcluster galaxy centroid. The offset of these centroids is 34 kpc (~8”). The subcluster and main cluster separation matches the currently observed value of 660 kpc.

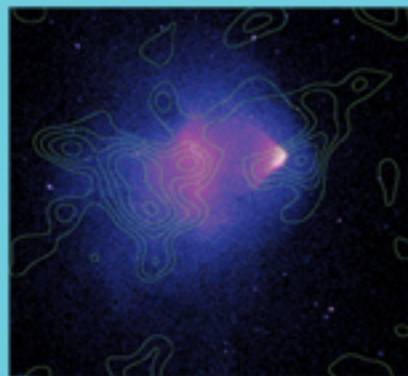

Figure 1: X-ray image of 1E 0657-56, with the weak-lensing mass map overlain.

RESULTS

To study the effects of varying we ran several merger simulations with varying , each initialized to reproduce the observed projected mass map at the current cluster separation. We find that the offset between the subcluster dark matter and galaxy centroids is strongly correlated with . For instance, if $/m=1$ cm^2 g^{-1}, then the offset is 34 kpc, whereas $/m=0.25$cm^{2}g^{-1} gives an offset of 7 kpc. Though the latest results for the centroids are currently being derived, the positional accuracy will certainly be within this range, giving an improvement over the tightest constraint on from the analytic estimates of $/m<1$ cm^2 g^{-1}. Furthermore, constrains from the survival of the sumbclump are improved in the simulations. We find that if $/m=1$ cm^2 g^{-1} then the M/L ratio of the subclump is dcreased by 38% of its inital value, whereas the analytic calculations estimate the same upper limit if the M/L ratio drops by 20-30%. If the M/L ratio is found to be consistent with with the main cluster and universal values to within 15% (and we interpret this as meaning that the subcluster has loss less than 15% of its mass during the merger) then the simulations show that $/m<0.5$ cm^2 g^{-1}. We therefore expect in the end to improve on the constraints given by the analytic estimates by *at least* a factor of two, possibly more, as new, more accurate results are obtained from the latest observational data.

DISCUSSION

We have presented several independent methods for estimating the self-interaction cross-section of dark matter using observations and simulations of the merging cluster E1 0657-56. Although the nature of dark matter is still unknown, its physical properties can have far-reaching astrophysical implications. Self-interacting dark matter has been invoked to explain the non-observation of cuspy mass profiles and large numbers of sub-halos within larger systems predicted by collisionless dark matter. Our initial results show that our code is capable of producing the expected results for collisional dark matter systems, suggesting that more detailed simulations will allow us to further constrain this important astrophysical parameter.

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