Calculating Time Since Pericenter of Merging Galaxy Clusters

Livia Darmawan
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Mentor: David Wittman
UC Davis Physics

The analog method developed by Dr. Wittman and his research group obtains information about clusters of merging galaxies through a series of programs which compare observed clusters to those in cosmological n-body simulations with similar known properties. One of the advantages of this method over other historical methods of analyzing clusters is that we are able to obtain an estimate of the time since pericenter. The times since pericenter of merging clusters are important pieces of information which can be employed in the study of dark matter. This is achieved through adding a program which extracts separation data of analogs to calculate the probable times since pericenter based on the likelihood of the analogs matching observed clusters.

I. BACKGROUND

A. Merging galaxy clusters

Galaxy clusters are systems that can contain hundreds to thousands of gravitationally bound galaxies. Besides galaxies, clusters are also comprised of gas and dark matter, the latter of which is thought to be the main source of gravity holding the cluster together [1].

A merger occurs when different clusters of galaxies experience gravitational attraction towards each other and come together in a collision. We study dissociative mergers, in which the gas, galaxies and dark matter in the clusters separate[1]. This process occurs over hundreds of millions of years. The separation between these components during a merger can be observed through a combination of x-ray imaging and gravitational lensing of clusters.

FIG. 1. X-ray and gravitational lensing of the Musket Ball Cluster shows gas in red, dark matter in blue

The dark matter halos which contain dark matter, galaxies and a mixture of galaxies and gas, are pulled away from each other while hot gas is left behind at the center of the collision. But because they are affected by each other's gravity, the halos will fall back towards each other, and continue in this back and forth motion [1]. The closest distance between the centers of mass of the galaxies and dark matter halos is defined to be the pericenter.

Observations of what happens to the dark matter during cluster mergers are of great interest because they can lead to a better understanding of the nature of dark matter.

B. Analog method

Cosmological n-body simulations, which simulate the evolution of galaxies over time lapses of hundreds of millions of years, are tools that can be used to study merging galaxy clusters. A method developed by Dr. Wittman and his research group searches a simulation for possible matches, or "analogs," to any known observed cluster based on known properties of the cluster.

The particular simulation being used is the Big MultiDark Planck Simulation, which simulates a dark matter universe. This simulation has been chosen for its large box size $(2.5\ \mathrm{Gpc/h})^3$ containing 3840^3 particles, encompassing redshift z=100 to z=0 (present day). Analogs of known clusters are found based on minimal inputs of mass, projected separation and relative radial velocity. When viewed from all possible angles, the probability of a match can be obtained as a function of the viewing angle. This in turn informs the probability of other dynamic properties of the merger [2].

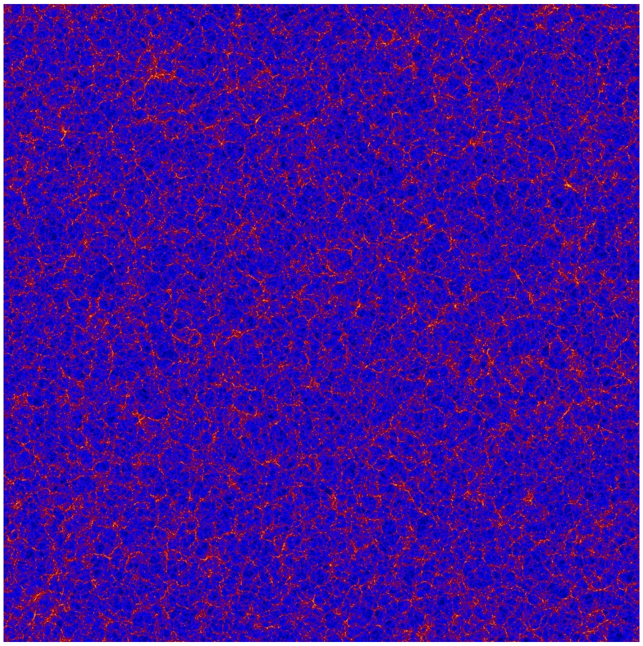

FIG. 2. Slice of BigMDPL simulation at z=0. Red structures represent dark matter mass distribution. Scale unknown.

The analog method offers several advantages over other methods of analyzing merging clusters such as the timing argument. Compared to such analytical methods that do not make use of simulation data, the use of a simulation captures variation caused by the large scale of the mergers, including the outside environment as well as the substructure within the clusters themselves. Simulations are also designed to factor in cosmologically motivated impact parameters. Simpler approximations assume a minimum impact parameter, implying that the separation vector is parallel to the velocity vector [2]. This does not account for the effects of gravity as two masses approach, by which the masses should be deflected from their original trajectory.

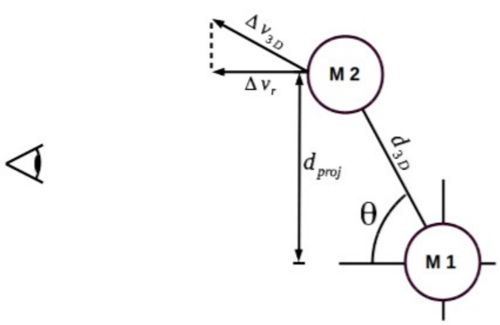

FIG. 3. A nonzero impact parameter accounts for a velocity vector Δv_{3D} not parallel to the separation vector d_{3D}. Inputs for analog search: mass 1, mass 2, projected separation d_{proj} and radial velocity Δv_r are defined here, along with the viewing angle theta.

Another advantage of the analog method is that it allows us to obtain an estimate of the time since pericenter, which is an essential piece of information because it affects the offset between the galaxies and dark matter halos, but it is difficult to measure due to the large timescale of the mergers [2]. The rest of this paper will detail how a solution to the time since pericenter was found, including the steps that built up to it.

II. ANALOG CODE

The programming for the analog method is split between a series of programs that achieve different steps of extracting data from the simulation, filtering to find halo pairs of interest, cataloging history of pairs, and calculating probabilities of matches and the resulting probabilities of dynamic properties of observed clusters. The time since pericenter is calculated using data filtered through these steps, so understanding them is essential to arriving at the solution.

A. Pre-existing code

Data from the Big MultiDark Planck simulation are accessible from an online database on www.cosmosim.org. An SQL query can be run on the site for mass, 3D separation, 3D velocity, and simulation-specific identifier data on clusters with a mass of over 6e13 solar masses, which is a large enough minimum size to account for all known clusters, within a chosen time frame in the simulation.

Programs have been written in Python and C++ to filter and catalog the data of interest. First, the original data obtained through the SQL query are searched for pairs of halos within 5 Mpc of each other, which we define to be the cutoff for merging pairs. These pairs are then filtered so that each possible pairing only appears once, and any double counts are removed. Once all unique pair data are compiled, catalogs are created of the separation and velocity data of each pair throughout different snapshots in the simulation. From this, the data can be further filtered for pairs that have only merged once.

The next steps in the analog method would be to run a program written to calculate the probability of an analog match for a chosen cluster, and another program to calculate the probabilities of dynamic properties of the cluster and display them graphically. But finding the time since pericenter requires a different process from calculating the probabilities of other properties of a cluster, because the pericenter occurs at a time in the simulation that is not readily identifiable. Thus the data files compiled from the pair history are the most directly relevant to this project.

B. Time since pericenter

The halo pair history files contain data of the separation between halos throughout different snapshots of the simulation. The first attempt to find the time since pericenter involved searching each pair for its pericenter using this data. For pairs merged in the current snapshot, pericenter was defined to be a separation of less than 0.5 Mpc with an outgoing velocity in the current snapshot. For pairs merged in a previous snapshot, we searched for a local minimum in the list of separations which was less than 0.5 Mpc. The snapshot at which this minimum occurred was then used to find the time since pericenter. Each snapshot corresponds to a redshift value which represents real time.

However, this approach had a lot of potential for error because between each snapshot in the simulation there is a significantly large time interval that is not equal between all snapshots. The time intervals ranged from a fraction of a gigayear to over a gigayear. Within that time frame there could be a lower minimum separation not accounted for.

To account for these gaps between the snapshots, we took three points of closest separation for each pair and interpolated through them by fitting a parabola through the points. The vertex of the parabola would then represent the separation and time of pericenter, which would be used to calculate the time since pericenter of an analog. The probable time since pericenter of any given cluster could be found based on the probability of an analog match.

III. RESULTS

The interpolation of separation vs. time improved our estimate of pericenter but raised more issues. The most obvious was the code sometimes returning a negative value for time since pericenter. To better understand the root of this problem, we graphed different sets of closest separation vs. time data. Figure 4 illustrates the root of this issue, which lies in a key difference in results of interpolation for pairs merged in the current snapshot versus pairs merged in the past. We observed that for cases of pairs merged in the current snapshot, the vertex of the parabola would occur at a time beyond present day in the simulation, and this would cause a negative result in the calculation of time since pericenter.

The most accurate estimate of pericenter would most likely occur at a time shortly before the corresponding real time to the current snapshot. This would be easier to see if we had finer time sampling.

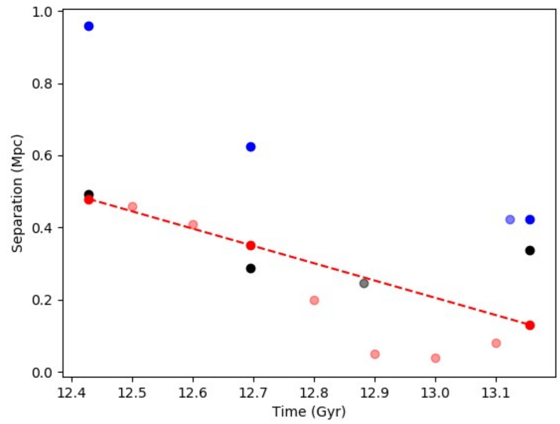

FIG. 4. Interpolation of separation vs. time using parabolic fit. Sets of blue, black and red opaque dots are closest separation points from simulation data. Blue and black transparent dots are results of parabolic fit. Interpolation of red points would have resulted in a vertex far to the right. Transparent red dots represent hypothetical results of finer time sampling.

The slope of the interpolation line, or more accurately the slope of the parabolic fit, theoretically represents the rate at which the separation between a pair of halos changes (merging or moving away).

IV. CONCLUSION

An extension of the analog code has been added to obtain an estimate of the time since pericenter of observed clusters. An improvement has been made by interpolating the data using a parabolic fit, but further improvements are required to improve the accuracy of the estimate.

V. ACKNOWLEDGEMENTS

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[1] David Wittman, *Merging Galaxy Clusters as Dark Matter Colliders* (2018)

[2] David Wittman, B Hunter Cornell and Jayke Nguyen, *Simulated Analogs of Merging Galaxy Clusters Constrain the*

Viewing Angle (2018)