Collisions Between Galaxies: The Cyber 205 as an Astrophysical Laboratory

Joshua Barnes
Piet Hut
The Institute for Advanced Study
Princeton, NJ 08540

Background

Before the advent of the supercomputer, astrophysicists were forced to function without traditional laboratories because their subject matter was both so vast and so distant. The supercomputer has made it possible to bring astronomy and astrophysics into the realm of experimentation like the rest of physics.

One area of astrophysics in which having a laboratory makes all the difference is the study of interacting galaxies. Stars do not directly interact very much with each other because they are so small, compared with the vast interstellar distances, that they very rarely collide. Galaxies, on the other hand, have a diameter which varies from one percent to several percent of their inter galactic distances. Since they run around somewhat randomly, entire galaxies will cause a lot of "traffic accidents."

Observation of the sky shows that several percent of all galaxies reveal clear signs of interactions with other galaxies. Indeed if we look hard enough we can see signs within most galaxies that at some point in the past they have interacted with other galaxies. If you want to compare it to walking around a city like Boston, you will see that a few percent of the cars have big dents while a large fraction of the cars have small scratches. Even if you visit Boston for only a few seconds this tells you a lot about the time average of the past history of collisions between cars. Similarly, while we live but for a few seconds on a cosmic time scale, if we look at the way galaxies appear right now in the sky, we have also a clear idea of their typical past interactions from a qualitative point of view.

The Problem

To become more quantitative we would like to use our computer as a laboratory and actually follow in some detail the interactions between galaxies. Not only does this begin to give us a better understanding of the past history of galaxies, it also may begin to shed some light on the problem of dark matter.

Most of the matter in the universe exists in a form that we don't understand. Stars and gas clouds that are directly visible by their radiated light account for only about ten per cent of the mass of the universe. About 90% of the matter which we "feel gravitationally" is in a form which is not directly visible. The problem of understanding the nature of this dark matter is really the central problem in all of astronomy.

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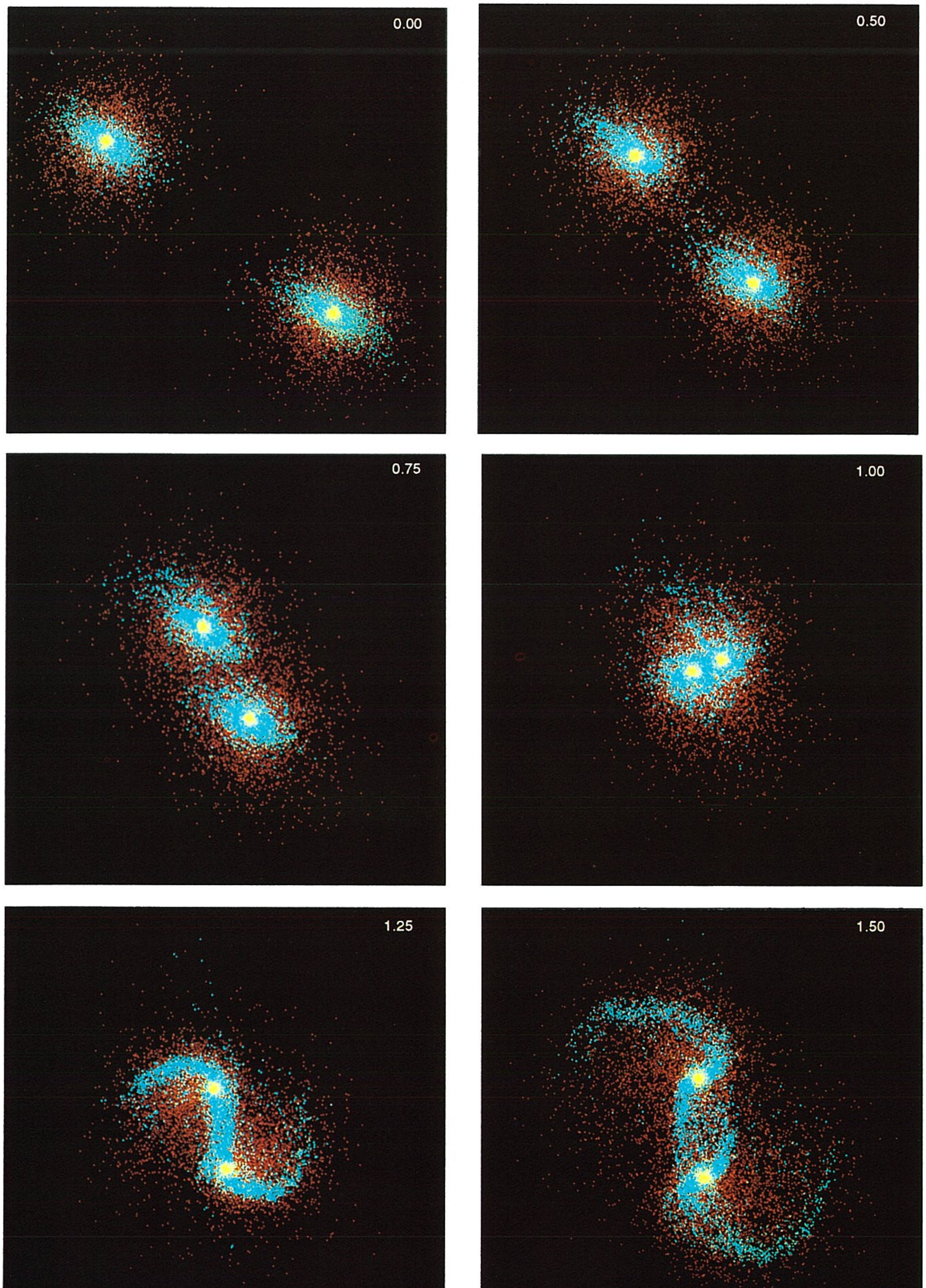
OVERLEAF ILLUSTRATION:

The following two pages show a simulated collision of two galaxies over a one billion year period.. Dark matter is shown in red, disk stars in blue and the galactic center stars in yellow. In the first picture in the sequence, the two galaxies are well separated but moving toward each other. By the second frame a spiral structure has begun to develop in their disks. As they pull closer together the spirals in the third frame begin to get a bit distorted. The fourth frame shows the moment of closest approach. At this point the two galaxies have actually penetrated each other's disks producing increased distortion. The next frame shows them pulling apart. Note the concentration of dark matter piling up behind the visible portion of each galaxy. By frame six the galaxies have reached their greatest point of separation. With frame seven the centers of the galaxies marked by the yellow cores have actually started to fall back together. Meanwhile the disk stars (blue) are being flung outward into two crook shaped features. The next few frames show the galaxies continuing to fall back together. With the ninth frame they have a second and final collision, after which they merge to form a single galaxy. The final frames show what happens to this single remnant over the next 400 million years. The central structure relaxes and turns very slowly, meanwhile the outer material is starting to fall back toward the center in two streamers of material which feed into the galaxy from opposite sides. (Time is indicated by numbers in upper right corner of each picture.)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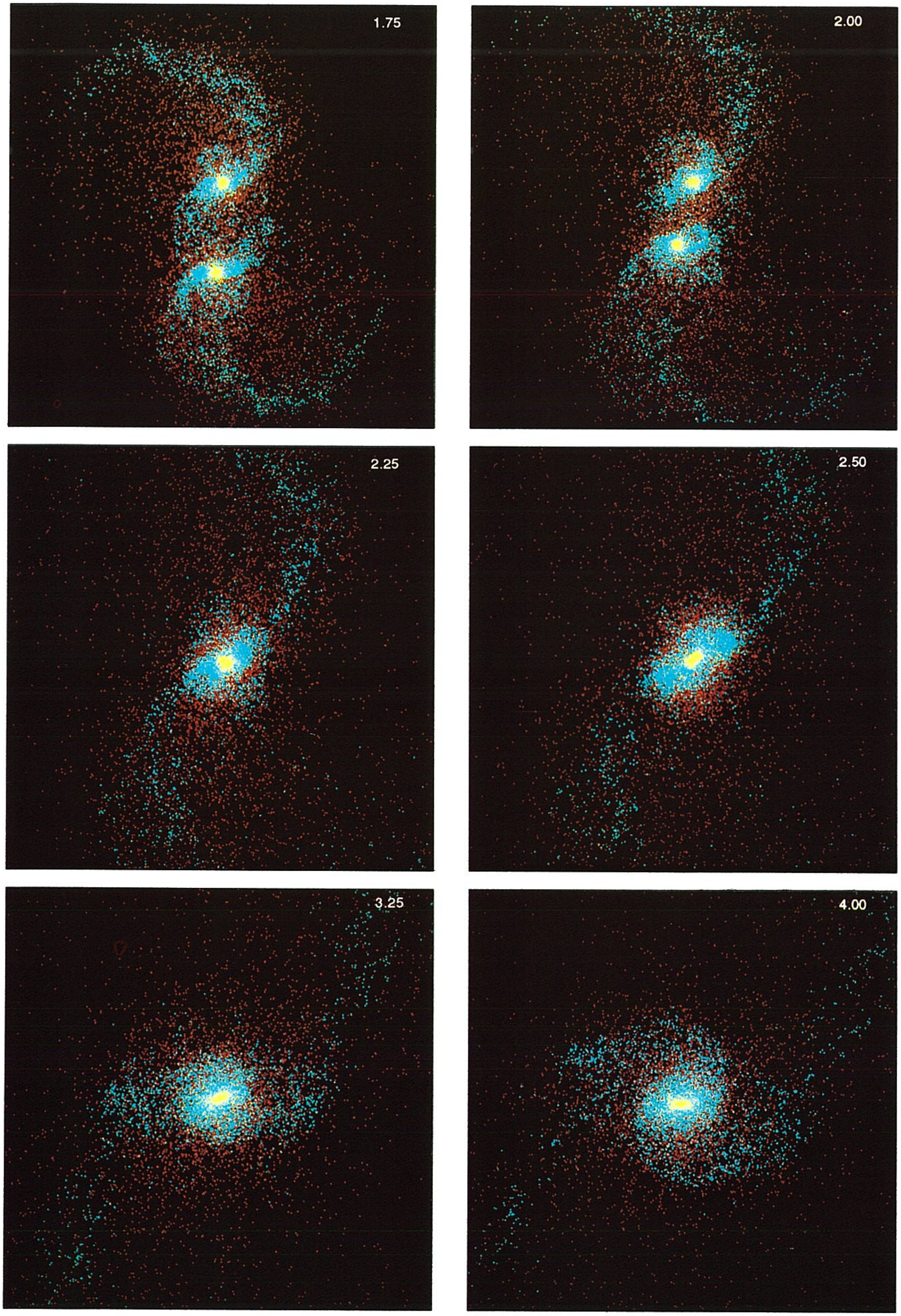
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The gravitational force that we may infer from the motion of stars within a star cluster is pretty much the gravitational force which the stars exert. But if we observe on a larger scale, a galaxy or group of galaxies, then we see a kind of motion which can be explained only by the force required by the existence of a much larger amount of mass.

Because direct exploration is out of the question, astronomers must observe the motions of the stars, defined by their positions and velocities. Then from this we can infer how much force is needed to keep the galaxies together given their motion. If galaxies move faster and faster, more and more force is needed to keep them together. Otherwise they would fly apart. So, if we look at a group of galaxies which presumably have been together for most of the age of the universe, by measuring the speed of the individual galaxies within the group we can calculate the forces needed to keep the group together. We can, at the same time, estimate the mass of the visible matter. Then we can establish the gravitational force exerted by the visible matter, and it turns out the force needed to keep such galaxies together is an order of magnitude larger than the force available from the visible matter.

So we have three broad choices. We could assume that most groups of galaxies were born rather recently and are now rapidly expanding. But many of the stars in these galaxies are far too old for this idea to work. We could hypothesize that the galaxies are bound together by some mysterious non-gravitational force with exactly the properties required to account for the observed velocities. Finally we could suppose that the force which binds galaxies together is ordinary gravitation, but that most of this gravitation comes from some kind of "dark matter" which, up to now, has escaped our direct observation, but which, as the dominant form of mass in the universe, provides the "glue" needed to keep the galaxies together.

To have some basis for deciding between these choices, we would like to find some corroborating evidence. One might suppose that there is little difference between a mysterious force and a mysterious form of matter, but that is not so. It is easier to propose non-gravitational forces, than to prove that such forces exist. On the other hand, if we assume the existence of dark matter which cannot be directly observed, but which obeys the known laws of physics -- and especially Newtonian gravity -- then we can look for other effects of this matter. Since the motions of individual stars in galaxies, and of individual galaxies in groups and clusters, provided the original motivation for the dark matter hypothesis, we should look at some different but related aspect of galactic dynamics for corroborating evidence.

One promising way to look for evidence of dark matter is by studying galactic collisions. What we would like to do is smash some galaxies together and "spill" some of the stars of the galaxies out to a larger area so that we can trace out the force field of the dark matter to which we normally have no access. Now in one sense this is the opposite of an elementary particle collision experiment where you smash particles together to break them up and see what is inside. With galaxies you smash them together because you want to see what is on the outside. What Rutherford first did to atoms to see what their internal constituents were, is what we do to galaxies to see what is the external distribution of matter which envelops them. The dark matter outside the galaxies forms a potential well in which the galaxies reside deep in the center. We would like to use some "star paint" to trace out the potential well in order to make its shape visible.

Right now there are many hypotheses about the nature of dark matter. The problem is to try and select which ones are plausible and which ones are not. One of the areas where the debate has been the sharpest is in deciding how much dark matter is required. One hope here is to make different computer models of the collisions of galaxies incorporating different amounts of dark matter. We can then compare the results to see which looks most like our real universe. In order to get results which are comparable to what we observe, we have to include some dark mass around the galaxies that we are modeling.

Results

If we are to see what role the collisions really play, we must understand how these galaxies are transformed by the collisions from one kind to another. We have found that if you compare calculations with, versus without, dark matter, the outcome is different in the following sense. Without the dark matter the galaxies stick together and eventually form one object, which is rapidly rotating because it has no way of getting rid of much angular momentum. On the other hand when a collision that includes dark matter is simulated, the remnant produced is not rapidly rotating. The dark mass acts as a sink for the angular momentum of the luminous stuff which is slowly rotating, if at all, with many stars oscillating back and forth along the major axis.

If we look at real galaxies, we find that some are spiral in shape while others are elliptical. In our experiments, when dark matter is assumed to be present, collisions of spiral galaxies do give us things that look like elliptical galaxies. So there is reason for thinking that there is indeed dark matter present and, two: that spiral galaxies do merge to form elliptical galaxies.

Both these hypotheses are linked into other pieces of evidence in astrophysics. One is the velocities of stars within individual galaxies which give us some evidence of dark matter there, and also the velocities of galaxies in groups and in small clusters which tells us that there is dark matter there as well. We also have cases where astronomers have studied a galaxy and have determined that it has recently merged with another galaxy to form an elliptical galaxy, as would be predicted by our computer models.

Methodology

The distribution of mass in a galaxy is modeled directly using a particle method with N of the order 16384. The gravitational field is computed using the O(NlogN) algorithm described by Barnes and Hut in Nature , volume 324, page 446.

This algorithm is based on a very old computing strategy known as divide and conquer. The earlier method would have been to add up the forces between each pair of particles. If you have 1000 particles you have a million interactions. However 10,000 particles imply 100,000,000 reactions which, in terms of computing requirements, rapidly excedes the limits of what is feasible. Instead, we lump many distant particles together and calculate a single interaction with that whole collection of particles.

Future Directions

It is fair to say that determining the nature of dark matter is *the* problem in all of astrophysics. It is also a problem with a bearing on the prospects of ever attaining a Grand Unified Field Theory for all of physics. In trying to establish a connection between astrophysics, cosmology and particle physics, the nature of dark matter is also the most fundamental question. The hypotheses that one prefers to explain the existence of dark matter also tends to determine one's view of cosmology.

One possibility is that the dark matter is some sort of fundamental particle which doesn't interact, making its existence known only via gravity. Several alternative forms of this idea exist: one that the dark matter was something with, initially, very little relative motion so that early in the universe when everything was rapidly expanding away from everything else, it was smoothly expanding. Then because it had no internal motion, gravity pulled little lumps of it together. These lumps attracted other lumps and before long there was very substantial mass.

A second alternative is that dark matter was something which was moving relativistically, such as a very light weight particle that would have had a lot of energy in the early universe. Such particles flew around at the speed of light until the expansion of the universe caught up with them. When this happened, gravity could again pull things together. Now because these particles have been flying about relativistically for so long they have smoothed the mass distribution, leaving only big gentle curves. So the kind of clustering that develops from this "picture" is very different. Great big structures come crashing together and then fragment to produce galaxies.

To some extent we can hope to test which of these alternatives is appropriate, by looking at the results of galaxy collisions to see if they really support the claim that there are halos of dark matter around individual galaxies. The result of our experiments seem to be that the galaxies do have individual dark halos although we haven't succeded yet in establishing just how much halo dark matter is needed. This clearly depends on what role one expects the dark matter to play. The existence of individual dark halos would imply that galaxies were built up from small scale to large scale structure.

There are still, however, many other possible forms for the dark matter which we are not yet in a position to test. For example, it is possible that the luminous parts of the galaxies formed first, and collected halos of dark matter later, or that the dark and luminous components formed from the same original stuff. Indeed there are perhaps as many different theories of galaxy formation as there are types of galaxies! Detailed numerical models can lead to some progress in understanding the formation and structure of individual galaxies. In the longer run, experimental results from numerical laboratories can help differentiate between the various theoretical possibilities, and perhaps suggest additional lines of observation and theoretical investigation.

Reference

Joshua Barnes, "Encounters of Disk Halo Galaxies", Astrophysical Journal, August 15, 1988