Halo-Stripping in Galactic Collisions

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ABSTRACT

Galactic collisions are normally modeled in a CDM model by assuming the DM consists of a small number of very massive objects. This note shows that the behaviour of a CDM halo during collisions depends critically on the mass of the particles that make it up, and in particular, all halo particles below a certain characteristic mass are likely to be lost.

Subject headings: galaxies: dark matter, merging galaxies
1. Introduction

There is now a sizeable literature on collisions between galaxies, and computer models
show a remarkable resemblance to observations of interacting galaxies (see, e.g. Barnes
1982). Typically these involve the numerical solution of N-body collisionless Boltzmann
equations, where \( N \sim 10^4 \). This implies that the effective mass of a dark-matter (DM) body
is \( 10^6 M_\odot \) and one may wonder whether the results are independent of this assumption.
In particular, it would be interesting to know whether the behaviour of cold dark matter
(CDM) halo particles in a collision is effectively the same whether they are massive
neutrinos or MACHOs.

In this note we point out that CDM haloes may behave in radically different ways
depending on the mass of the particles. Specifically haloes composed of particles lighter
than a certain mass \( m_0 \) \( (m_0 \sim 10^{16} \text{ kg}) \) will be stripped off a galaxy during a collision, while
heavier ones will remain with the galaxy and would presumably become part of a merged
galaxy. We derive a specialized form of the Chandrasekhar dynamical friction formula
which is the gravitational analogue of the Bethe-Bloch formula, and then apply this to a
highly idealized galaxy collision. Finally we offer some speculations on how this will affect
galaxy populations.

2. Dynamical Friction

Consider a particle of mass \( \mu \), which is incident on a gravitationally interacting gas
consisting of particles of mass \( m \) and number density \( n \). The dynamical friction formula
(Chandrasekhar 1943) can be written

\[
\frac{d\vec{v}_m}{dt} = -2\pi \ln \left(1 + \Lambda^2\right) G^2 \mu (m + \mu) \int f(v) \frac{(\vec{v} - \vec{v}_m)}{|\vec{v} - \vec{v}_m|^3} d^3v
\]  
(1)
We take the gas to be at rest, and the incident particle to be moving with a velocity $v$ and simplify to the case $m = \mu$. None of these assumptions are critical to the argument. It is then easy to transform (1) to

$$\frac{dE}{dx} = -\frac{8\pi G^2 \mu^2 \rho}{v^2} \ln (\Lambda) \quad (2)$$

where $\rho$ is the mass density of the gas. The argument of the log is very large, so the log can be replaced by a dimensionless constant $C_0$. The resulting equation can be derived from the Bethe-Bloch (see, e.g. [Rossi 1952]) equation by a judicious change of variables. Note the occurrence of the $\mu^2$ term, which is crucial to the following argument: qualitatively one can see that the cross-section is proportional to $\mu$ and the mean momentum transfer is also proportional to $\mu$. It is also somewhat counter-intuitive that the force increases as $\frac{1}{v^2}$ at low velocities. To see how this affects a galactic halo, consider the collision process shown below.

. The galaxies are assumed to have a spherically symmetric halo of particles of mass $\mu$ and density $\rho(r)$, and to be moving with a relative speed of $v_\infty$. It is then trivial to integrate (2) to give

$$v^4 = v^4_\infty - 16\pi C_0 G^2 \mu \int \rho(r) ds \quad (3)$$

where the integral is along the path followed by the particle. To proceed further we need to have a definite model for the density distribution in the galaxy. The model must give flat rotation curves out beyond the edge of the visible galaxy, and yet have a finite mass. For simplicity we choose

$$M(r) = M_\infty \left( 1 - e^{-\left(\frac{r}{r_0}\right)} \right) \quad (4)$$
which gives a density function

\[ \rho(r) = \rho_0 \frac{e^{-y}}{y^2}, \quad y = \frac{r}{r_0} \]  \hspace{1cm} (5)

(This is, of course, not a good approximation for the core of a galaxy, but fortunately this is not relevant to the following argument). If the rotational speed of the galaxy is \( v_0 \) we get

\[ M_\infty = \frac{r_0 v_0^2}{G}, \quad \rho_0 = \frac{M_\infty}{4\pi r_0^3} \]  \hspace{1cm} (6)

This allows (4) to be integrated giving

\[ v^4 = v_\infty^4 - 32\pi G^2 \mu r_0 C_0 I(b_0), \quad I(b_0) = \int_{b_0}^{\infty} \frac{e^{-y}}{y \sqrt{y^2 - b_0^2}} dy \approx \frac{e^{-b_0}}{b_0} \]  \hspace{1cm} (7)

where \( b_0 = \frac{b}{r_0} \) is the scaled impact parameter and the approximation for the integral is good to about 50\% for the range \(.01 < b_0 < 2\). By inspection of one can see that a particle will only be stopped in a galactic collision if its mass was larger than the characteristic mass \( \mu_0 \) given by

\[ \mu_0 = \frac{v_\infty}{2 \left(2\pi G^2 \rho_0 C_0 I(b_0)\right)^\frac{1}{4}} \]  \hspace{1cm} (8)

3. An idealized Galaxy Collision

To give some idea of the value of \( \mu_0 \), we can take plausible values of \( r_0 = 50 \) kPc and the orbital velocity \( v_0 = 200 \) k\( ms^{-1} \) and further assumes that the galaxies have a velocity \( v_\infty = 100 \) k\( ms^{-1} \) when they collide. This gives rise to \( M_\infty = 10^{42} \) kg \( \sim 10^{12} M_\odot \), \( \rho_0 = 10^{-22} \) kg m\(^{-3} \) and \( C_0 \approx 300 \) (for \( \mu = 10^{-27} \) kg) to 30 (\( \mu = 10^{30} \) kg). This gives rise to a characteristic mass \( \mu_0 \approx 10^{16} \) kg. Loosely speaking, any particle with a mass of less than \( \mu_0 \) would not be stopped in the collision. Note that this argument does not apply to gas or dust, which are affected by conventional friction. Hence we may expect that baryonic
matter would behave in the way predicted by the N-body simulations, and in particular
MACHOs would not be lost to the merged galaxy. Possibly asteroids which are sufficiently
massive that the conventional frictional force on them would be relatively small and which
were not gravitationally bound to a solar system would also be lost.

However, particles which interact only via gravitational interactions only, which means
neutrinos or WIMPs (we use WIMPs generically in what follows) would behave very
differently. WIMP haloes would be stripped off during a collision of this kind, with a time
scale of \( \frac{r_v}{v_\infty} \sim 10^8 \) yrs. To see what would happen to the stars in such a collision, consider
a collision between two identical spiral galaxies, which occurs in such a way that the cores
coalesce immediately. Assuming that the luminous matter obeys a similar mass distribution
function

\[
\rho (r) = \rho_0 r_0^2 \frac{e^{-r/r_1}}{r^2}
\]

so that the galaxy is entirely luminous matter at the centre, and \( r_1 \approx 10 \) kPc is the
radius of the luminous matter. In this case, stars at the centre of the galaxies would be
essentially unaffected by the loss of the halo, stars out to a critical radius \( R \sim 1.59r_1 \) would
be forced into increasingly elliptical orbits and any stars beyond \( R \) would no longer be
bound.

The most serious weakness in this model is the assumption that the target gas is at
rest. Since obviously nothing is known about the velocity of WIMP haloes, it is difficult
to correct this. One might argue that the WIMPs form a gas with a BB temperature of
(say) 2 K, which would correspond to velocities in the range of a few \( ms^{-1} \), in which case
the assumption is obviously valid. Alternatively the WIMP halo could co-rotate with the
central galaxy, or (more plausibly) form a gravitationally self-bound system, in which case
the virial theorem gives
The latter two assumptions both imply speeds of \( 200 \text{ kms}^{-1} \) which are comparable to the collision speeds. This would require much more detailed modeling than is possible here, but one would expect that some fraction of the halo with a small velocity in the final rest system of the merged galaxy would be retained, while the majority would be stripped.

The idea that haloes are stripped in collisions is in qualitative agreement with two results. Firstly Dubinski et al. 1996 show that tidal tails form during galaxy mergers appear to be considerably longer than would be predicted by N-body simulations. They note that the best estimates of dark matter derived from tidal tails in merging galaxies such as NGC 4038/39 and NGC 7252 imply a value about 1/3 of that derived from spiral galaxies. This could be understood if much of the halo material is lost after the collision. If, as is generally believed, elliptic galaxies are formed by collisions of spirals, they should be almost devoid of haloes. Galaxies in a cluster would have lost much of their DM haloes during repeated collisions, and the DM would be bound to the cluster as a whole. This is, of course, consistent with observations of (e.g.) the Coma cluster.

One could regard this as strong circumstantial evidence that the main component of haloes are WIMPs. Obviously if this can be confirmed by more detailed models, it would be of considerable importance.

4. Conclusion

This calculation suggests that the behaviour of the DM haloes during a galactic collision depends critically on the mass of the particles that make it up. If the DM objects are relatively light (both neutrinos and WIMPs are light in this context), then the halo
will be lost totally, while heavy haloes would be retained as predicted by the N-body
simulations. In other words, this process provides a way to differentiate between a particle
type solution and a MACHO type solution to the DM problem.

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