Fossil structure in the galactic halo:

Trying to reconstruct the formation history of the Milky Way

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Those that have looked up in the heavens will have noticed a band of silvery light across the sky, which is known as the milky way. This light has its origin in millions of distant stars that are too far to be resolved with the naked eye. This "milky way" is what one observes looking edge on into the disk of our Galaxy. For myself, and perhaps many other astronomers, the fascination for astrophysics lies in the combination of the incredible beauty of the heavens, an example of which is the milky way shown in Figure 1, and the prospect of being able to explain how the Universe works under the simple laws of physics.

There are many billions of galaxies like the Milky Way in the Universe. Understanding how these systems formed is one of the fundamental questions in Astrophysics today. Popular theories of galaxy formation and evolution propose that galaxies are the result of mergers and accretion of smaller sub units, that come together through the action of gravity. This 'hierarchical' (bottom-up) build up of structure in the Universe has gained substantial observational support in the last twenty years, mostly from observations of very distant galaxies caught in the process of forming, as shown by the Hubble Space telescope (see Figure 2).

Any successful theory of galaxy formation should also be able to reproduce the properties of the Milky Way. Our Galaxy constitutes a benchmark in galaxy formation studies, since we have access to multidimensional information (like the positions and velocities of individual stars) which is not available for other systems. This wealth of data has the power of strongly constraining any scenario of galaxy evolution.

In the context of the hierarchical scenario, understanding how the Milky Way was assembled is equivalent to reconstructing its 'genealogical family tree'. This contains information on the progenitors of our Galaxy, that is, on the mergers it has experienced,the properties of the merging objects, when these events took place,etc. These in turn must have determined its shape, the ages and chemical composition of the stars that form it, their motions... In this article I will try to address how we might be able to reconstruct the Milky Way merging history. Clearly, the ultimate test of the hierarchical formation of our Galaxy consists in actually finding the signatures of the mergers the Milky Way experienced over its life. Thus we need to understand what those signatures are, and what are the observational requirements to recognise them.

Let us start by studying in some detail how mergers of galaxies proceed. As an example, consider the simpler case of a satellite galaxy orbiting the Milky Way, shown schematically in Figure 3. Like in the problem of the Moon orbiting around the Earth,

▲ **Fig. 1:** Panoramic view of the sky showing the Milky Way. Individual stars are shown as white dots. The "Milky Way" clouds, actually the combined light of dim, unresolved stars in the densely populated galactic plane, are interrupted by dramatic dark dust lanes (Lund Observatory, Sweden).

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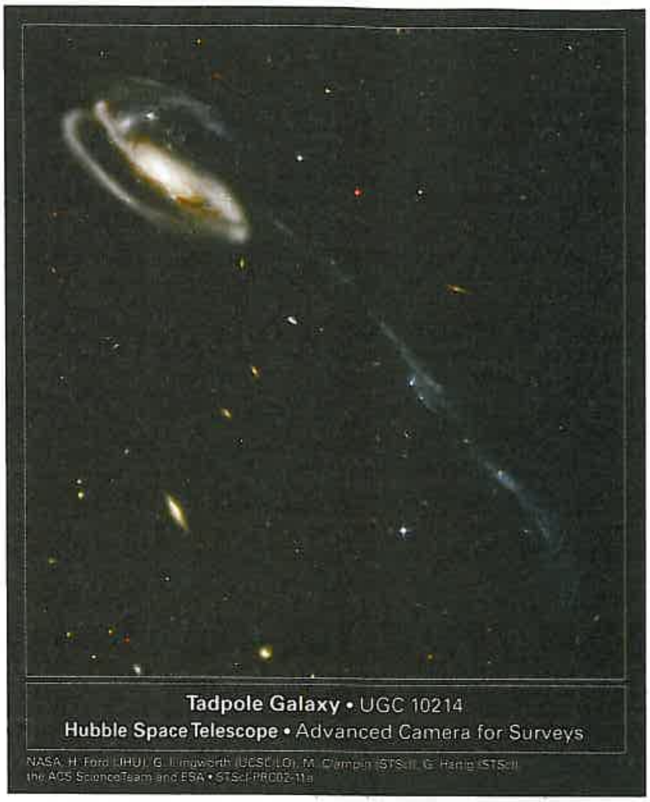
▶ **Fig. 2:** This picture of the galaxy UGC 10214 was taken by the Advanced Camera for Surveys (ACS) on the Hubble Space Telescope. It shows long streamer of stars originated in the compact galaxy visible in the upper left corner of the image. Strong gravitational forces from the interaction created the long tail of debris, consisting of stars and gas that stretch out more than 280,000 light-years (STSci).



gravity is the main driving force. The critical difference lies in the fact that we are dealing with N-body systems, where N is very large. Although gravity is a relatively simple force, the fact that it is long-range,and that one has to deal with large numbers of particles (representing stars for example), implies that one often has to recur to numerical simulations to properly model the evolution of galactic systems.

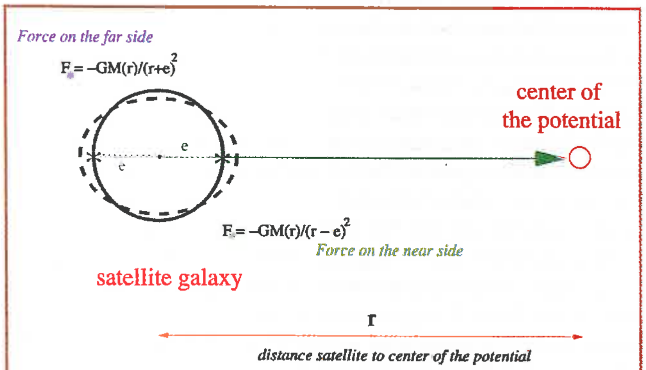
In the case we are interested in (a small galaxy orbiting a larger one), the stars in the satellite system feel a differential gravitational pull caused by the Milky Way galaxy. Due to the finite size of the satellite the force it feels on the side closer to the Galactic centre is different from that on the opposite side, which produces a deformation of its shape. This deformation is analogous to the tides the Earth experiences due the Moon's gravitational pull.The stars in the satellite may become unbound if their internal energy is positive. Once they are released, they become, as it were, part of the Milky Way galaxy. They continue moving on similar orbits as the satellite but may now drift away from it, as shown in Figure 4. This drift is caused by the fact that their energies are slightly different from that of the satellite, as are their orbital frequencies.

An ensemble of disrupted satellite galaxies, leaving behind the characteristic trails of stars shown in Figures 2 and 4, will give rise to a spheroidal component. Stellar halos, which are a diffuse spheroidal component of galaxies, are thus a natural reservoir of the debris of past mergers.

Conservation laws are very powerful tools in physics, and they are particularly useful in the context of trying to recover the history of a Galaxy. One such law is the conservation of energy. Let us consider our problem of a small ensemble of stars (a satellite galaxy) orbiting around an (otherwise static) galaxy. Initially the stars in the ensemble are all strongly concentrated in space and share essentially the same motion. This implies that they all have very similar energies. If the energy is a conserved quantity (an assumption which may not always hold), then at the present time all the stars in the ensemble will also have the same energy. Thus they would still be clumped in energy space. Clearly, if one would be able to measure directly the energies of the stars in our Galaxy one should discover the distribution is not smooth but formed by many lumps, which simply reflect the systems that gave rise to our Milky Way. However, it is not always possible to determine the energy of the stars in the Galactic halo, since it implies knowledge of the Galactic potential,as well as the 3D location and motion of the star. Thus the question shifts to understanding how do such "energy" lumps look like in observable coordinates, like those directly accessible through observations. How does the distribution of stars evolve in time? What is their spatial distribution at the present time, what is their velocity distribution, are there any hints of substructure?

Another useful conservation law is stated by Liouville's theorem,which describes the conservation of volume (or density) inphase-space: $dV = d^3x\, d^3v$ = constant. As we mentioned above,once a star is released from its parent system, it starts to drift away (see Figure 4). Thus d^3x increases in time. Since the volume is conserved in phase-space, this implies that locally d^3v has to decrease in time. Thus stars originating in the same system, should have very similar motions even after a very long time has passed since they were released from their parent system. They would be predicted to be clustered in structures that we call *streams*.

What is the observational evidence in favour of the scenario described above? First of all, out of the thirteen or so known satellite galaxies of the Milky Way, three of them are currently showing signs of being strongly perturbed by tidal forces. The Large and Small Magellanic Clouds have lost a good fraction of their gas content,which now forms a stream which closely follows the orbit of the system, similar to what is shown in Figure 2. Another very spectacular example is the Sagittarius dwarf galaxy which is

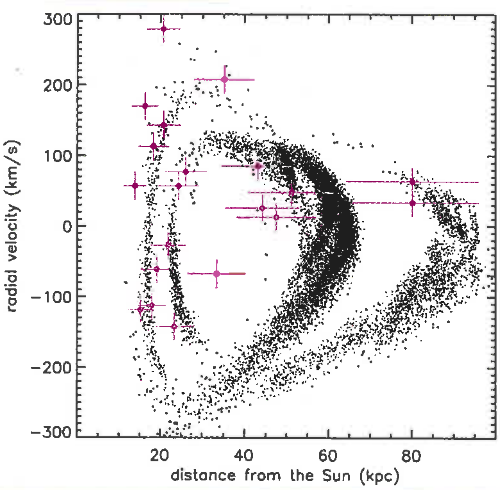


▲ **Fig. 3:** Schematic picture showing the tidal force exerted on a small satellite due to a larger (in this case) central object. The force on a star in the side closer to the centre of the potential is $F_{near} = -GM(r)/(r_{sat} - \epsilon)^2$, while for a star located on the far side it is $F_{far} = -GM(r)/(r_{sat} + \epsilon)^2$, implying a softer pull. This differential force is what produces the deformation in the shape of the satellite galaxy.

▲ Fig. 4: Numerical simulation of the disruption of a small galaxy, probably similar to the Sagittarius dwarf, a current satellite of the Milky Way. The panel on the left shows the initially strongly concentrated satellite. As time goes by, the satellite is progressively destroyed by the gravitational pull of the large galaxy, giving rise to trails of stars which closely follow the orbit of their progenitor. The panel of the right shows that eventually the streams overlap spatially, and the stars become part of a roughly spherical halo around the central galaxy. The image in the centre of each panel corresponds to the neighbouring disk galaxy Andromeda, which closely resembles the Milky Way (Picture from Bill Schoening, Vanessa Harvey/REU program/NOAO/AURA/NSF).

being completely torn apart just now, and which will not be visible as a coherent unit the next time it comes close to the centre of the Galaxy, in about 10^9 years.

But was this also a common phenomenon in the past? What fraction of the stars that are now part of the Galaxy came aboard such a satellite like those we see today? How do we gain access to that information? For the outer halo, where the dynamical timescales are long, trails of stars, such as those shown in Figure 4, should remain coherent until the present day. Therefore the positions of stars should suffice to determine how lumpy the outer stellar halo is. There are several efforts going on to try to discover these structures. The Spaghetti Project Survey (the analogy clearly is that the halo is a bowl of spaghetti!) is one of such projects that aims to identify fossil relics of destroyed galaxies. The collaboration is carrying out a large-scale study optimised to identify distant halo stars on the basis of their peculiar (characteristic) colours (which are due to their low metal-abundance). These stars are then observed with a spectrograph to determine their velocity along the line of sight. This additional piece of information has enabled them to discover streams associated to material lost by the Sagittarius dwarf galaxy indifferent passages near the Galactic centre, as shown in Figure 5.



▲ Fig. 5: A slice of phase-space r vs v_r for a model of the disruption of the Sagittarius dwarf galaxy. The particles from this model of Sagittarius are shown here as black dots. The solid circles with error bars correspond to halo stars observed by the Spaghetti collaboration. The agreement between the observed location and motion of most of these stars suggests that they were in the past part of the Sagittarius dwarf galaxy.

A second very large survey which has started to map the distribution of stars in the Galaxy is the Sloan Digital Sky Survey. It has in the past two years revealed tantalising substructures in the galactic halo, most of which can also be linked to the disruption of Sagittarius.

Most of the action, however, is expected to have taken place closer to the centre of the Galaxy, and at very early times. Recovering fossil structures in the inner stellar halo, or in the vicinity of the Sun,is considerably more difficult. The key issue is that the timescales are very short in this region of the Galaxy, and soon streams overlap in space, as shown in the last panel of Fig. 4 and in Fig. 5. This makes very difficult distinguishing observationally one stream from the other on the basis of positional information alone, and even the knowledge of the velocity along the line of sight, which is relatively easy to measure, does not improve the situation. The degeneracy can only be broken with 6 dimensional information, so that also the motions projected in the sky are known. However, measuring proper motions requires either a very long time span (of the order of fifty to a hundred years) or very accurate positional information (better than 1 microarcsecond), which can only be achieved from space.

Currently there are not very many large samples of halo stars with sufficiently accurate motions to enable us to break up the velocity distribution into the hundreds of streams expected. The HIPPARCOS satellite provided proper motions of about 100 halo stars, which combined with ground-based observations, allowed astronomers to discover the first direct indication of a past merger in the Solar neighbourhood: a small galaxy probably similar to current satellites of the Milky Way. To do recover more such events, and be able to determine the relevance of this process in the build up of our Galaxy, astrometric satellite missions are necessary. The European Agency satellite GAIA is one such mission, that will measure with very high accuracy the motions of millions of stars in our Galaxy and in our nearest neighbours. Such large samples of stars with six-dimensional phase-space information will undoubtedly shed light on the fundamental questions concerning the origin and evolution of galaxies. Missions such as GAIA will allow us to reconstruct the genealogical family tree of the galaxy that we call our home: the Milky Way.

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