The co-planarity of satellite galaxies delivered by randomly aligned cold mode accretion streams

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ABSTRACT
Recent observations have shown that the majority of the Andromeda galaxy’s satellites are aligned in a thin plane. On the theoretical side it has been proposed that galaxies acquire their gas via cold streams. In addition, numerical simulations show that the same streams also deliver satellites. Assuming that cold streams are the major source of satellite systems around galaxies we calculate the probabilities to find a certain fraction of satellites within a thin plane around the central galaxy of the host halo. Using simple geometrical considerations and adopting a random orientation of the streams we demonstrate that the vast thin disk of satellites detected around Andromeda can naturally be explained within this framework. In fact, without any satellite scattering, three streams or less would lead to too many satellites in the thin plane, compared with the observations. Four to seven streams reproduce the observations very well. Thin disks of satellites might therefore provide important relic information about the early phases of gas accretion of galaxies and can be interpreted as indirect observational evidence for the cold stream paradigm.

Key words: cosmology: theory – galaxies: evolution – galaxies: formation – galaxies: high redshift – methods: numerical

1 INTRODUCTION
Our understanding of how galaxies form has changed substantially in recent years. A decade ago it was thought (Blumenthal et al. 1984; Rees & Ostriker 1977; Silk 1977; White & Rees 1978) that galaxies collect their baryons through diffuse gas, spherically symmetrically falling into dark matter haloes and being shock-heated as it hits the gas residing in the halos, the so-called hot mode accretion. Whether the gas eventually settles into the equatorial plane, forming a galactic disk was depending on the mass of the dark halo. Below a critical mass, the gas could cool efficiently, forming a disk galaxy, while for larger masses the cooling time would be longer than the Hubble time, leading to structures that resemble galaxy clusters with a large baryon fraction in the hot, diffuse intergalactic gas component. Recent theoretical work and simulations (Fardal et al. 2004; Birnboim & Dekel 2003; Birnboim & Dekel 2003; Kereš et al. 2005; Dekel & Birnboim 2006; Ocvirk & Pichon & Tevssier 2008; Dekel et al. 2009a, 2013) have however shown that at high redshift (z ≥ 2), galaxies acquire their baryons primarily via cold streams of relatively dense and pristine gas with temperatures around 10^7 K that penetrate through the diffuse shock-heated medium, the so-called cold mode accretion. These streams peak in activity around redshift 3. Having reached the inner parts of the host halo they will eventually form a dense, unstable, turbulent disc with a bulge where rapid star formation is triggered (Agertz, Tevssier & Moore 2004, 2011; Dekel, Sari & Ceverino 2009a; Ceverino et al. 2012; Cacciato, Dekel & Genel 2012; Genel et al. 2011).

N-body simulations suggest that about half the mass in dark-matter haloes is built-up smoothly, suggesting that the baryons are also accreted semi-continuously as the galaxies grow (Genel et al. 2011). Hydrodynamical cosmological simulations also show rather smooth gas accretion, including mini-minor mergers with mass ratios smaller than 1:10, that brings in about two thirds of the mass (Dekel et al. 2009a). The massive, clumpy and star-forming discs observed at z ∼ 2 (Genzel et al. 2008; Genel et al. 2011).
Cold accretion streams are just about to be directly observed. Goerdt et al. (2010) used cosmological hydrodynamical AMR simulations to predict the characteristics of Lyα emission from the cold gas streams. The Lyα luminosity in their simulations is powered by the release of gravitational energy as the gas is flowing inwards with a rather constant velocity. The simulated Lyα-blobs (LABs) are similar in many ways to the observed LABs. Some of the observed LABs may thus be regarded as direct detections of the cold streams that drove galaxy evolution at high z. Observations Rauch et al. (2011) and new AMR simulations incorporating radiative transfer support this model Rosdahl & Blaizot (2012), Goerdt et al. (2012) made theoretical predictions about the likelihood of observing these streams in emission which have very recently really been observed Bouche et al. (2013).

Danovich et al. (2012) find that at the few virial radii of the vicinity of the galaxy, the streams tend to be confined to a stream plane, and embedded in a flat pancake that carries ~ 20% of the influx. There are on average three significant streams, of which one typically carries more than half the mass inflow. Given the fact that galaxies grow by cold stream accretion, the question arises whether some observational signatures of this phase are still detectable in present-day galaxies.

Ibata et al. (2013) showed in a seminal observational paper the existence of a planar subgroup of satellites in the Andromeda galaxy (M 31), comprising about half of the population. The structure is at least 200 kiloparsecs in radius, but also extremely thin, with a perpendicular scatter of less than 12.6 kiloparsecs. Radial velocity measurements reveal that the satellites in this structure have the same sense of rotation about their host. This shows conclusively that substantial numbers of dwarf satellite galaxies share the same dynamical orbital properties and direction of angular momentum. Intriguingly, the plane they identify is approximately aligned with the pole of the Milky Way’s disk and with the vector between the Milky Way and Andromeda.

Following up on this Bowden, Ewans & Belokurov (2013) argued that a thin satellite disc can persist over cosmological times if and only if it lies in the planes perpendicular to the long or short axis of a triaxial halo, or in the equatorial or polar planes of a spheroidal halo. In any other orientation, the disc thickness would double on ~ 5 Gyr timescales and so must have been born with what they call ‘an implausibly small vertical scaleheight’.

Several scenarios have been proposed in order to explain the origin of planar satellite systems. Dwarf galaxies might be accreted in groups. D’Onghia & Lake 2003, Li & Helmi 2008. Alternatively, the disk of satellites might be the tidal debris of a major merger with a gas-rich galaxy with the tidal arms condensing into tidal dwarf galaxies. Wetzstein, Naab, & Burkert 2005, Bournaud, Duc & Emsellem 2008, Pawlowski, Kroupa & de Boer 2011. This scenario is however in conflict with the observational evidence of substantial amounts of dark matter, dominating the kinematics of dwarf spheroidals (see however Kroupa 1995, Pawlowski, Pflamm-Altenburg & Kroupa 2012). Interestingly, coherently rotating, quasi-planar distributions of satellites have also been found in cold-dark-matter simulations Lovell et al. (2011), Keller, Mackey & Da Costa 2012). This indicates that satellite great planes might be a natural result of how galaxies accrete material and substructure from the cosmic web. It is this idea, that is the motivation for our paper. We demonstrate that thin planes of substructure, consistent with the observations of Ibata et al. (2013) are in fact expected if galaxies are fed by cold, satellite loaded streams. Evidence for such an accretion mode in cosmological simulations is shown in section 2, where we also present a simple geometrical model to analyse the probability to generate a satellite disk with given thickness and satellite fraction, given a certain number of randomly oriented cold streams. Section 3 shows our results. Section 4 presents the conclusions.

2 CALCULATIONS

We know that gas and, for our purposes more interestingly, also subhaloes enter a host halo via smooth accretion streams Dekel et al. 2009a). In figure 1 we show maps from hydrodynamical AMR simulations of high redshift (z ~ 2.5) high mass (Mvir > 1011 M⊙) galaxies from two suites of cosmological simulations: the Horizon-MareNostrum simulation Ocviˇ r, Pichon & Teyssier 2008, hereafter MN) and the Ceverino, Dekel & Bournaud 2010, hereafter CDB) suite of simulations. The circles indicate the virial radii. Clearly visible are three cold streams, funnelling gas into the centre of the galaxy. One can also see several clumps, embedded in the streams. Those are satellite galaxies which are entering the host halo via the streams. Note that there are no clumps outside a stream, indicating that the build-up of a satellite system is stream driven.

Suppose now that galaxies and their satellite systems form in the focal point of a number m of randomly oriented cold streams. What is then the probability that a certain fraction of satellites lies within a thin plane around the central galaxy of the host halo? Ibata et al. (2013) find through observations that 15 out of Andromeda galaxy’s 27 satellites are within a plane with 200 kpc radius and 12.6 kpc vertical rms scatter. This corresponds to an angle of 3.6 degree. They exclude two out of those 15 subhaloes since those are counterrotating. Since our analysis does not take into account the orientation of the rotation we will compare our analyses to the ratio 15/27 ≃ 56% in this paper.

In order to work out the likelihood to have of order 56% of satellites in a plane as thin as 3.6 degree we have performed Monte Carlo simulations, drawing randomly oriented streams and calculating the probabilities of having a given ratio of subhaloes within a plane of certain thickness. Underlying our calculations are the following assumptions:

1. All subhaloes enter the host halo through cold streams only, as proposed by Dekel et al. 2009a.
2. Any host halo has between three and eight streams
3. The streams themselves are randomly distributed over the whole sky as seen
from the centre of the host halo. We are aware of studies which present evidence that already the streams seem to lie in a single plane (Dekel et al. 2009a; Danovich et al. 2012). It is therefore a conservative assumption to distribute the streams randomly with equal solid angles on the sky carrying equal probabilities of having a stream. (4) Each stream is loaded with an equal amount of subhaloes. Here we ignore varying loading factors amongst the streams because we want to keep the analysis as simple as possible. As mentioned above, for a small number of streams this is again a conservative assumption. We refer the interested reader to a forthcoming paper which will develop a more sophisticated model that will also discuss kinematical properties of stream-driven satellite disks. (5) The streams will hit the centre of the host halo directly head on, i.e. they have no significant impact parameter with respect to the central galaxy. The affect of reasonable, non-zero impact parameters as inferred from cosmological simulations on the rotational properties of satellite systems will be discussed in the subsequent paper. (6) The subhaloes will stay on the same orbits as defined by their stream. This assumption is motivated by the fact that the potential well of the host haloes in consideration are relatively shallow with respect to the inflow velocity of a stream. We therefore expect scattering processes to be of minor importance although a quantitative evaluation of this effect will require detailed investigation of inflow speeds as function of the depth of the central potential well of the system (Goerdt et al., in preparation).

Using this assumptions we have performed a large number of Monte Carlo calculations. We start a Monte Carlo calculation by fixing the total number \( m \) of streams, with \( m \) in the range of three to eight. We then draw a large number of random stream orientations. As mentioned earlier, randomly oriented means, that an equal solid angle of the sky as seen from the centre of the host halo carries a stream with an equal probability. Also all streams must cross the centre of the host halo and the position of one of the streams does not have any influence on the position of the other streams. For each of the sets of streams we conduct a grid search over the whole sphere for the ‘optimum’ plane. Two adjacent planes in the grid search are never further apart than 0.2 degree. “Optimum” means that we determine the plane with the smallest opening angle \( \psi \) for a given number \( n \leq m \) of the \( m \) streams. Note that there are different optimal planes for different values of \( n \). In practice, the program runs through the following steps: Given one of the planes from our grid search mentioned above, we calculate the angles of each of the \( m \) streams relative to this plane. The resulting \( m \) angles are sorted according to their value. The highest value indicates the angle within which all \( n = m \) streams belong to that one plane. The second highest value indicates the angle within which a number \( n = m - 1 \) streams belong to that plane. We collect the values of the minimal angle \( \psi \) for each set of streams for each value of \( n \). We then proceed to the next test plane of our grid search.

3 RESULTS

In figure 2 we show the cumulative distribution functions of having \( n \) out of \( m \) streams in a plane with an opening angle \( \psi \). Each panel corresponds to a different total number \( m \) and each of the coloured dashed curves shows a different value of \( n \). The vertical black line at 3.6 degree indicates the observation of Ibata et al. (2013). The two triangles on that line indicate the intersections with those predicted \( n/m \) curves.
Figure 2. The coloured dashed lines show the cumulative distribution $P$ of having $n$ out of the total $m$ streams within an angle $\psi$. The solid black vertical line indicates the angle of 3.6 degree estimated for Andromeda’s thin satellite disk (Ibata et al. 2013). The two triangles show the intersection of this vertical line with the two curves which are most closest to the observational value of 56% (15 out of 27). They indicate the cumulative distribution function and the likelihood that the observed fraction of streams lie in a single plane with at most the observed angular deviation.

Table 1. Quoted are for all possible total number of streams $m$ the two values for $n$ whose ratios are just above ($n_{\text{upper}}$) and just below ($n_{\text{lower}}$) the observed ratio of 15/27 $\simeq$ 56%. In the last two columns we quote the cumulative probability $P$ that $n$ out of $m$ streams lie in a single plane with a deviation of less than the observed 3.6 degree.

| $m$ | $n_{\text{upper}}$ | $n_{\text{lower}}$ | $P_{\text{upper}}$ | $P_{\text{lower}}$ |
|-----|---------------------|---------------------|--------------------|--------------------|
| 3   | 2                   | 2                   | 1.0                | 1.0                |
| 4   | 3                   | 2                   | 1.0                | 0.56               |
| 5   | 3                   | 2                   | 1.0                | 0.88               |
| 6   | 4                   | 3                   | 0.99               | 0.25               |
| 7   | 4                   | 3                   | 1.0                | 0.47               |
| 8   | 5                   | 4                   | 0.71               | 0.10               |

that lie most closely to the fraction 15/27 $\simeq$ 56% of Andromeda’s satellites that have been found in the thin plane. These triangles therefore show upper and a lower values for our predicted probabilities. In table 1 we summarise our results.

Since we assumed that all the streams pass through the galaxy centre, two streams will always lie on a perfect plane. The ’$2 / m$’ lines in figure 2 therefore are always at probability $P = 1.0$. For a three stream scenario we would expect at least 67% of the satellites to lie within one plane. Since two, three or four stream configurations are most commonly seen in cosmological simulations (Danovich et al. 2012), we can say already that there is nothing surprising about the configuration seen around the Andromeda galaxy. On the contrary, the fact that so little satellites lie on a thin plane rules out a two stream or a three stream scenario for the Andromeda galaxy, unless secular evolution or other processes move some of the satellites out of that plane. Turning the argument around, the fact that we observe a large fraction of satellites in a thin plane can be seen as indirect observational evidence for the cold mode accretion stream scenario proposed by Dekel et al. (2009a) and that scattering events are not efficient, at least for the Local Group.

Note also that here we have used a conservative model of equal satellite loading. Allowing for a varying fraction of satellite galaxies in each of the streams would significantly strengthen our argument. For the three stream scenario, for example, the two streams which carry the most and the second most satellites will always lie in one plane, carrying then more than 67% of all satellite galaxies together.
4 CONCLUSIONS

Inspired by recent observations we investigated the probability that a certain fraction of subhaloes lies within a thin plane around the central galaxy of the host halo within the framework of the cold stream scenario. We performed Monte Carlo simulations, drawing randomly orientated streams and assuming that the satellites stay on orbits parallel to the stream, leading to the following results:

- The configuration seen around the Andromeda galaxy is a natural result of cold stream accretion. A plane as thin as observed can be generated with probabilities as high as 50% to 100% for two to five streams, which is the most common configuration in cosmological simulations.
- Without scattering of dwarf satellites, the Andromeda galaxy must have been fed by more than three streams otherwise we would expect more than only 56% of its satellite galaxies to lie within a very thin plane. The most likely number of streams ranges from four to seven or eight. If Andromeda’s satellite system was produced by three streams in fact a large number of objects must have been scattered out of the thin plane and it would be interesting to investigate whether and how this scattering process affects the internal structure of these satellites.
- Since the cold stream feeding mechanism guarantees an initial disc that is born with a remarkable small vertical scaleheight, scattering processes as discussed by Bowden, Evans & Belokurov (2013) will most likely play only a minor role.
- The observations by Ibata et al. (2013) can be interpreted as indirect observational evidence for the cold mode accretion scenario (Dekel et al. 2009a). There is no need for an ab initio coplanar configuration of streams since random orientation of the streams will produce a sufficiently thin disk already.
- An additional implication in the case of three or four streams would be that the satellites should naturally distribute themselves into two inclined planes.

We are aware that the current analyses has its limitations. One interesting point is that impact parameters for the streams hitting the central galaxy are not taken into account. Including impact parameters would introduce rotation into the satellite system. A detailed investigation of this is planned in a forthcoming paper that will also include a study of the typical impact velocities of satellites, riding cold streams. Another problem could be that we do not model the transition from radial orbits as implied by the cold stream model to more circular orbits as observed. These processes would also force satellites out of the plane. No limitation but a rather conservative choice is the assumption of constant satellite loading factors from stream to stream. As discussed in the last section introducing such a variation would even strengthen our argument.

We conclude that the special spatial alignment of Andromeda’s satellite galaxies can naturally be explained by cold stream accretion and simple geometry. Satellite alignments around galaxies can be seen as indirect observational evidence for the cold stream paradigm and provides important information about the accretion history of galaxies.

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