2.3 The Andromeda satellite galaxies

In order to study the three-dimensional distribution of the satellite system of Andromeda it is most convenient to transform their position vectors relative to the observer into an Andromeda-centric coordinate system (see also McConnachie & Irwin 2006b). A detailed description of the transformation is given in Section 2.1.4 in the most general way. Two different data-sets for the distances of Andromeda and its satellites were incorporated: the first data-set as published by McConnachie & Irwin (2006b, MI data-set, see their table 1) where most of the distances were derived using the tip of the red giant branch method using ground based telescopes (McConnachie et al. 2005). This data-set can be considered as homogeneous data. The other data-set as given by Koch & Grebel (2006, KG data-set, see their table 1): they compiled a list of HST-based distance measurements. The data are given in Table 2.5 for both data-sets converted to Andromeda-centric coordinates.

Figs. 2.8 and 2.9 show an Aitoff projection of the satellite distribution on the Andromeda sky similar to Fig. 2.3 for the Milky Way. The projected error bars due to the combined uncertainties in the distance measurement of the satellites and Andromeda are shown, which are given by

$\sigma = \sqrt{\sigma_{M31}^2 + \cos^2(\beta) \sigma_{sat}^2}$, \hspace{1cm} (2.31)

where $\sigma_{M31}$, $\sigma_{sat}$ are the distance uncertainties of Andromeda and its satellite, respectively, and $\beta$ is the angle between the lines-of-site to Andromeda and its companion. In each figure, the positions derived from the other data-set are shown with small open symbols for comparison. Note the voids in the regions $l_{M31} < 180^\circ$, $b_{M31} < 0^\circ$ and $l_{M31} > 180^\circ$, $b_{M31} > 0^\circ$ in both figures. As shown by McConnachie & Irwin (2006b), these regions are only marginally obscured by the Milky Way disc (see their figure 1), the region of maximum obscuration is near IC 10 at $(l_{M31} = 103^\circ$, $b_{M31} = 45^\circ)$.

Similar to the case of the Milky Way, more faint dwarf galaxies probably remain to be found for Andromeda within the next few years. One of these discoveries was reported by Zucker et al. (2007): the dSph And X is comparable in luminosity to And IX, however the distance determination was difficult. Zucker et al. (2007) gave a distance of $667 \pm 30$ kpc to $738 \pm 35$ kpc. Three satellites, And XI – XIII, were reported in another recent paper by Martin et al. (2006). No distances could be determined for the individual galaxies, but combining their colour-magnitude diagrams and assuming all to have the same distance, Martin et al. (2006) derived a combined distance of $740 – 955$ kpc. Next, Majewski et al. (2007) reported the discovery of a dSph in the vicinity of Andromeda, named And XIV. They estimated a heliocentric distance of $630 – 850$ kpc. Two further dSphs were reported by Ibata et al. (2007), And XV and And XVI, and most recently the discovery of And XVII was reported by Irwin et al. (2008). Given the large distance uncertainties for all these recently discovered dwarf galaxies, we do not include these in our analysis but discuss them later.
Figure 2.8: The Aitoff projection of the locations of the M31 satellites in the Andromeda-centric coordinate system for the MI data-set. Symbols are chosen as in the previous section: red circles mark dSphs, green diamonds dIrrs. Blue hexagons now mark dE/cE galaxies, and the location of M33 is shown by the blue pentagram. The small open circle mark the corresponding positions for the KG data-set. The projected distance errors due to the combined uncertainties in the distance measurement of the satellites and M31 are shown. The position of the Milky Way is indicated by the triangle.

Figure 2.9: As Figure 2.8 for the KG data-set, small open circles now showing the corresponding positions for the MI data.
Table 2.5: Parameters of the Andromeda satellites: the first five columns contain a running number, the name, the morphological type, the sub-sample belonging (morphological or kinematical subsample), and the absolute luminosity in the V-band of the satellite. Columns 6 – 8 list the positions in Andromeda-centric coordinates (§2.1.4) for the first data-set (MI), and the 9th and 10th columns list the radial and perpendicular components of the measured line-of-sight velocity relative to Andromeda (§3.3.1). In the columns 11 – 15, the same data are provided for the second data-set (KG). The asterisks mark satellites for which the possible poles of the angular momentum vector can be restricted (§3.3.1). For the newly discovered satellite galaxies (running numbers larger than 17) distance data was taken as reported in the respective discovery paper, cited in the column with the luminosity data.

Continued on the next page.
Table 2.5 – Continued

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<th>No</th>
<th>Name</th>
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<th>$L_V$ [10$^6$ L$_\odot$]</th>
<th>$l_{M31}$ [°]</th>
<th>$b_{M31}$ [°]</th>
<th>$r_{M31}$ [kpc]</th>
<th>$v_t$ [km s$^{-1}$]</th>
<th>$v_r$ [km s$^{-1}$]</th>
<th>$l_{M31}$ [°]</th>
<th>$b_{M31}$ [°]</th>
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<th>$v_t$ [km s$^{-1}$]</th>
<th>$v_r$ [km s$^{-1}$]</th>
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<td>20</td>
<td>And XIII</td>
<td>dSph</td>
<td>0.05$^{(vi)}$</td>
<td>312.3</td>
<td>−37.6</td>
<td>136</td>
<td>-</td>
<td>-</td>
<td>315.6</td>
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<td>-</td>
<td>-</td>
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<tr>
<td>21</td>
<td>And XIV</td>
<td>dSph</td>
<td>0.2$^{(vii)}$</td>
<td>250.6</td>
<td>−48.2</td>
<td>162</td>
<td>-</td>
<td>-</td>
<td>256.6</td>
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<td>−36.9</td>
<td>176</td>
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<td>65.3</td>
<td>55.8</td>
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References: (i) Mateo (1998); (ii) McConnachie & Irwin (2006a); (iii) Zucker et al. (2004); (iv) van den Bergh (1999); (v) Zucker et al. (2007); (vi) Martin et al. (2006); (vii) Majewski et al. (2007); (viii) Ibata et al. (2007); (ix) Irwin et al. (2008)
The innermost twelve satellites of Andromeda (without counting M33) lie within \( \approx 269 \) kpc, the approximate virial radius of Andromeda, \( r_{\text{vir}} \), which is approximately of the same order as that of the Milky Way. We assume LGS 3 to be the twelfth satellite, although for the KG data-set And VI is actually closer to the centre. This will be addressed later (this Section and §3.3.2). The results of the fits are given in Table 2.2. For the MI-data the distribution is triaxial and more prolate, while for the KG data-set the distribution is found to be triaxial and more oblate, which is reflected in the further analysis, too. Figs. 2.10 and 2.11 show an edge-on view of the fitted planes and a view rotated by 90° about the polar axis of Andromeda, as well as a face-on view onto the fitted disc for the two data-sets (compare to Fig. 2.4 for the Milky Way). As can be seen the recently discovered dSph And X that was not incorporated in the fitting (marked by a smaller symbol near the centre of the plots), is located close to the fitted plane. If we just recalculate the rms-heights of the fitted disc, now including And X, it increases only slightly to \( \Delta = 46.6 \) kpc for the MI data-set, \( \Delta = 47.2 \) kpc for the KG data-set. Interestingly, also the three very recently discovered satellites And XI – And XIII (Martin et al. 2006) all lie very close (\( \approx 10 \) kpc for the MI data, \( \approx 30 \) kpc for the KG data) to the fitted disc when using a mean combined distance of 847.5 kpc albeit with large uncertainties.

For the applied error method (Table 2.3) the distance of Andromeda is not varied. This would only affect the distance of the plane from the origin. Compared to the spherical standard distance derived for the Milky Way, it is a factor of ten larger for the M31 system, which is not surprising given the much larger uncertainties in the relative distances M31 – satellite. The principal axes come out in good agreement with the poles of the single fits.

However, the ODR method yields poles that are far away from the poles found with the ALS method (Table 2.2). The difference is totally dominated by the large distance uncertainties, which are here not aligned within the fitted plane as in the case of the Milky Way. Instead they are systematically aligned along the line-of-sight from the Milky Way to Andromeda. The components in the direction to the Milky Way are weighted down and the fitted plane appears to be nearly perpendicular to the direction from the MW to M31, a result of the systematic dependencies of the covariances.

McConnachie et al. (2005) showed that the satellite distribution is significantly offset towards the direction of the Milky Way. This offset is also visible in Fig. 2.10, right panels. The offset is reflected by the large distance from the centre of Andromeda along the direction of the normal for the fitted planes when using the ODR method, due to the nearly face-on orientation of the fitted disc. In contrast, the disc-like distribution found with the ALS method is more edge-on, i.e. the systematic offset as identified by McConnachie et al. is within the plane.

As for the Milky Way, 10 000 bootstrap re-samplings for both data-sets of M31 are performed to test the robustness of the plane. The principal axis of the distribution is \( (l_{\text{M31}} = 75.5°, b_{\text{M31}} = -31.9°) \) \( [(83.1°, -30.0°)] \), being in good agreement with the original fit. We derive a shape parameter \( \gamma = 0.6 \) [2.9] and a strength parameter \( \xi = 3.1 \) [2.6], the spherical standard distance is \( \Delta_{\text{sph}} = 38.6° \) [27.9°] (numbers for the MI[KG] data-sets). While for the KG data-set the distribution of the directions of fitted normals for the bootstrapped sample is found to be clustered (\( \gamma > 1 \)), for the MI-data it is found to be a girdled distribution (\( \gamma < 1 \)). Fig. 2.12 shows a smoothed \( (l_{\text{M31}}, b_{\text{M31}}) \) scatter plot of the distribution
of the fitted normals for the MI data-set: there is a distinct peak about the principal axis and a second, weak over-density can be seen nearly 90° off, being the origin of the girdled distribution. The KG data-set does not show a secondary maximum.

And VI has approximately the same distance from Andromeda as LGS 3, both lying close to the approximate virial radius. Including And VI in the fitting routine for the KG-data, where it is actually closer to the centre of M31 than LGS 3, dramatically changes the picture. The pole of the fitted normals is clearly offset from the fits without And VI, the distance of the fitted plane is significantly offset from the centre of Andromeda, and the axis ratios do change significantly: $b/a = 0.63$ and $c/a = 0.57$. More importantly the clustering found for the bootstrapping without And VI for the KG-data disappears completely. If the satellite was within a planar-like distribution, the bootstrapped distribution should become similarly or even more tightly concentrated, as it did when including the UMa dwarf galaxy for the Milky Way. Instead, it gets very weak: $\gamma = 0.3$ and $\zeta = 1.7$. Therefore we treat And VI as an outlier.

In contrast to the Milky Way satellite system, for Andromeda the spherical standard distance derived with the applied error method is of the same order as for the bootstrap method which is a result of the large distance uncertainties for M31 and its satellites. So the results may well be affected by the still too large distance uncertainties for both, Andromeda and its satellite galaxies.

### 2.3.1 Morphological motivated subsample of Andromeda satellites

Koch & Grebel (2006) found a very pronounced polar disc-like feature for a morphologically motivated subsample of early-type dwarf galaxies. Their procedure was as follows: they first fitted a plane to all seven dSph galaxies in their data-set and then excluded And II (at a distance of $r_{M31} = 160$ kpc < $r_{vir}$) as an outlier because of its large distance to the fitted plane. This disc-like feature of six dSphs was found to be statistically highly significant, albeit we argue that their derived statistical significance is not unbiased (Sects. 2.1.2, 2.1.3, & 2.4.3). Next they included all other morphologically similar galaxies, three dEs and one cE (M32), again finding a disc-like feature with high statistical significance. In a last step they excluded two of the three dEs, but included one transitional type object, the dIrr/dSph Peg DIG at a distance of 410 kpc > $r_{vir}$, because of its close proximity to the disc-like feature found before$^{(d)}$. They also found that smaller spiral galaxy M33 is comprised by the plane of their sub-subsample, though not included in the fitting.

Indeed we confirm an amazingly thin configuration in the KG data when using this sub-subsample consisting of M32, And I, And III, NGC 147, And V, And VII, And VI, And IX, and Peg DIG. In Tables 2.2 – 2.4 we refer to the sub-subsample without Peg DIG as mss8 (morphological subsample of eight satellites). We exclude Peg DIG because it is well outside the approximate virial radius of M31. The fitted configuration is shown in Fig. 2.14. As can be seen, M33 is indeed located very closely to the fitted plane. For the KG data-set the pole of the fitted plane is $(l_{M31} = 168.0°, b_{M31} = -26.7°)$, with a distance from the centre $D_p = 1.6$ kpc, an rms-height $\Delta = 9.4$ kpc, and with axis ratios $c/a = 0.09$ and

$^{(d)}$However, also note the different scaling of the axes in their figure 3 which makes the distributions appear more planar-like than they truly are.
2.3 The Andromeda satellite galaxies

$b/a = 0.68$. For the weighted ODR method the results are very similar (see Table 2.2). M33 is located very closely to this fitted plane. Including Peg DIG for completeness results in $(l_{M31} = 163.0^\circ, b_{M31} = -27.3^\circ)$, with a distance from the centre $D_p = 1.2$ kpc, an rms-height $\Delta = 13.1$ kpc, and with axis ratios $c/a = 0.09$ and $b/a = 0.45$. But, this distribution ($b_{M31} = -27.3^\circ$) is not as polar aligned as claimed by Koch & Grebel (2006) due to the incorrect transformation to the Andromeda-centric coordinate system used by them (§ 2.1.4). Also note that, from the Milky Way, we are basically looking face-on onto this fitted plane, which is an important clue as we will show later.

Using the MI data-set without Peg DIG (MI mss8) leads to $(l_{M31} = 177.0^\circ, b_{M31} = -24.1^\circ)$, $D_p = 34.9$ kpc, and $\Delta = 29.2$ kpc (Fig. 2.13); including Peg DIG we find $(l_{M31} = 182.4^\circ, b_{M31} = -23.2^\circ)$, $D_p = 35.1$ kpc, and $\Delta = 29.1$ kpc. For this data-set the fitted plane is not as thin as for the KG data, and the offset from the centre of M31 is remarkably larger than the rms-height of the fitted plane. As can be seen in Fig. 2.13, there is now another dE (NGC 147, marked by the blue hexagon to the right of the plane) remarkably offset from the fitted plane.

Further insight comes from the AE test (Table 2.3). When applied to the morphological sub-subsample, the derived spherical standard distance is $\Delta_{sph} = 21.5^\circ$. This is a very large uncertainty in the location of the poles of the fitted normals, a factor three larger than for the full set of twelve satellites within the approximate virial radius used before. For the MI data-set, $\Delta_{sph} = 12.5^\circ$ is of the same order as for the full data-set.

In order to test the robustness of the results, a bootstrap analysis for the sub-subsample without Peg DIG is performed, now using 5 000 re-samplings accounting for the smaller number of possible distinct bootstrap samples ($^3N_{tot} = 6 231$ for $n = 8$). The results are given in Table 2.4. The principal axes are in agreement with the individual fits. The distribution of directions of bootstrapped normals is marginally clustered and concentrated. However the spherical standard distance for the bootstrapped sample is remarkably smaller than for the AE test. This indicates that the systematic uncertainties of the distances are larger than the intrinsic scatter of the fitted disc for the KG data. For the MI data-set the bootstrapped distribution is found not to be clustered but of transitional type. The spherical standard distance is significantly larger than for the KG data-set.

The recently discovered dSph And X is also found to be off the disc-like structure of the mss8 subsample for the KG data-set. For a heliocentric distance of 702.5 kpc its distance from the fitted disc is $\approx 87$ kpc ($> 9\sigma$; And II, excluded as an outlier by Koch & Grebel, is $\approx 127$ kpc away). To be within $\pm 10$ kpc from the disc, And X would have to be at a heliocentric distance of $\approx 786 – 808$ kpc. For the MI data-set And X’s distance to the fitted disc is $\approx 32.7$ kpc. And X is located on the near side of M31 to the Milky Way, thus adding to the systematic offset of the M31 satellite system towards the barycentre of the Local Group (McConnachie & Irwin 2006b).

We thus find that the apparent disc-like configuration of the dSph/dE satellite sub-subsample for Andromeda as proposed by Koch & Grebel (2006) is present for their data-set only and cannot be reproduced using the MI data-set. The nearly face-on alignment relative to the Milky Way results in distance uncertainties basically perpendicular to the fitted plane (Figs. 2.13 & 2.14). The thin configuration disappears when shifting the satellites...
Analysis of the spatial distribution of satellite galaxies

along their line-of-sight in accord with the distance uncertainties as done in the AE test. Comparing the results for the AE test and the bootstrapping suggests that the systematic uncertainties caused by the distance-measurement errors are larger than the intrinsic scatter of the distribution. Thus the thin disc-like configuration found may be just a chance alignment for the KG data-set, but its existence is not completely ruled out.

2.3.2 Kinematical motivated subsample of Andromeda satellites

In Section 3.3.2 we identify a subsample of Andromeda satellite galaxies that might have a common stream motion based on the intersection of their orbital poles (cf. also Lynden-Bell & Lynden-Bell 1995, Palma et al. 2002, and McConnachie & Irwin 2006b). Applying ALS to fit a plane for this kinematically motivated subsample of nine satellites (M32, NGC 205, And I, NGC 147, And II, NGC 185, IC 10, LGS 3, and IC 1613), but for the time being excluding IC 1613, the pole comes out to be located at \((l_{\text{M31}} = 69.9^\circ, b_{\text{M31}} = -35.2^\circ)\) \([\{(l_{\text{M31}} = 73.6^\circ, b_{\text{M31}} = -35.0^\circ)\} \) (MI[KG]-data-set), with axis ratios \(c/a = 0.12\) and \(b/a = 0.50\) \([c/a = 0.15\) and \(b/a = 0.71\)], i.e., a highly oblate (disc-like) configuration in both data-sets (Table 2.2). The pole is very close to the pole found for the full sample of twelve satellites within the approximate virial radius. In Figs. 2.15 and 2.16 it is clearly visible that also some satellites are excluded here, shown by open symbols, which lie spatially close to the initially fitted plane. Including the very distant (and possibly bound) satellite IC 1613 outside the approximate virial radius of Andromeda, we find the pole of the fitted normal to be located at \((l_{\text{M31}} = 74.4^\circ, b_{\text{M31}} = -40.5^\circ)\) \([\{(l_{\text{M31}} = 74.7^\circ, b_{\text{M31}} = -40.6^\circ)\} \), with axis ratios \(c/a = 0.10\) and \(b/a = 0.35\) \([c/a = 0.11\) and \(b/a = 0.43\)]. The latter axis ratio, leading to a more prolate configuration, is totally dominated by this one very distant satellite (IC 1613). We concentrate our further analysis on the sample of eight satellites without IC 1613, because it is located outside the approximate virial radius of Andromeda. We refer to this subsample in Tables 2.2 – 2.4 as kss8 (kinematic subsample of eight satellites).

Applying the AE test to the kss8 subsample, the direction of the principal axis is \((l_{\text{M31}} = 70.5^\circ, b_{\text{M31}} = -35.2^\circ)\) \([\{(l_{\text{M31}} = 74.2^\circ, b_{\text{M31}} = -40.6^\circ)\} \), with a spherical standard distance \(\Delta_{\text{sph}} = 2.4^\circ\) \([\Delta_{\text{sph}} = 1.6^\circ\) (KG [MI] data). The location of the principal axis is in good agreement with the individual fits above, and \(\Delta_{\text{sph}}\) is for both data-sets significantly smaller than for the full data-sets, and also an order of magnitude smaller than for the mss8 subsample (§ 2.3.1).

Performing the bootstrap analysis with 5000 re-samplings for the kinematically motivated subsample yields shape parameter \(\gamma = 5.9\) and strength parameter \(\zeta = 4.7\) \([\gamma = 14.9,\ zeta = 4.2\) \]. For both data-sets the distribution of the directions of the fitted planes of the bootstrapped data are strongly concentrated and clustered. The derived spherical standard distance is \(\Delta_{\text{sph}} = 9.8\) \([\Delta_{\text{sph}} = 11.5\), indicating that the systematic effects caused by the distance uncertainties are smaller than the internal scatter as derived by the bootstrapping.

Even though the morphologically motivated subsample (§ 2.3.1) has a smaller rms-height \(\Delta\) than the kinematically motivated subsample for the KG-data, and thus appears as a ‘thinner’ disc, the bootstrap analysis shows that the latter one has a more pronounced planar-like feature. The strong clustering is found in both data-sets. We have therefore uncovered a sample of eight M31 satellites (nine if IC 1613 was included) which span a very pronounced disc-of-satellites that is probably rotationally supported.
2.3 The Andromeda satellite galaxies

Figure 2.10: The Andromeda satellite system as seen from infinity for the MI data. An edge-on view (top-left panel), and a view rotated by 90° about the polar axis (top-right panel), as well as a face-on view (bottom-right panel) onto the fitted plane, derived using the ALS method, are shown as in Fig. 2.4 for the MW system. The recently discovered dwarf spheroidals And X – And XVII are marked by smaller symbols; these were not incorporated in the fitting. M33, which was also not incorporated in the fitting, is marked by the star. The other symbols are chosen as in Fig. 2.8. The distance uncertainties along the line-of-sight are indicated by the grey sticks. In addition, the grey shaded area indicates the projected region where potentially some satellite galaxy detections may be hindered by foreground MW structures (see also McConnachie & Irwin 2006b, their figure 1).
Figure 2.11: As Figure 2.10, plane-fit (ALS) for the KG data.
2.3 The Andromeda satellite galaxies

Figure 2.12: A smoothed \((l_{M31}, b_{M31})\) scatter plot of 10,000 bootstrap samples for the innermost twelve Andromeda satellites for the MI data-set ranging out to LGS 3 as Fig. 2.6. The principal axis of the distribution is located at \((l_{M31} = 75.5^\circ, b_{M31} = -31.9^\circ)\). The plot is shown 30\(^\circ\) off-centre from the principal axis. An additional contour line for the density estimate of 0.25 indicates a weak secondary maximum.
Figure 2.13: Plot as before for the MI data, now showing the results of the fitting for a morphologically motivated sub-sample (mss8) as proposed by Koch & Grebel. Satellites not incorporated in the fitting are marked with open symbols.
2.3 The Andromeda satellite galaxies

Figure 2.14: As Figure 2.13, plane-fit to the mss8 subsample for the KG data.
Figure 2.15: Plot as before for the MI data, now showing the results of the fitting for a kinematically motivated sub-subsample kss8. Satellites not incorporated in the fitting are marked with open symbols.
2.3 The Andromeda satellite galaxies

Figure 2.16: As Figure 2.15, plane-fit to the kss8 subsample for the KG data.
2.4 Statistical significance of disc-like distributions

In order to study the possible physical nature of the Milky Way and Andromeda satellite system, the statistical significance of the observed anisotropy, given a parent distribution, needs to be quantified. According to the null-hypothesis, the parent distribution ought to be a dark matter subhalo distribution, which may be spherical, oblate, prolate, or triaxial, and the positions of the satellite galaxies are randomly drawn from this parent distribution. To evaluate the significance of planar distributed satellite systems we compare the bootstrapped samples of the observed distribution with bootstrapped data of random samples from the parent distribution. For this we first create spherically isotropic distributions, where the radial linear probability density is proportional to \( \rho(r) \propto r^{-p} \), \( p = 2 \) \((\Rightarrow \rho_{\text{sph}}(r, \theta, \phi) \propto r^{-q}, q = 4)\), consistent with the radial distribution found for the Milky Way (Kroupa et al. 2005) and Andromeda (Koch & Grebel 2006). Random oblate, prolate, or triaxial ellipsoidal distributions with axis ratios \( c/a \) and \( b/a \) are then constructed by scaling the components of the random spatial position vectors while keeping the volume of the ellipsoid invariant,

\[
\begin{pmatrix}
{x'}
\end{pmatrix}
= f_V \begin{pmatrix}
\frac{b}{a} x \\
\frac{c}{a} y \\
\frac{1}{a} z
\end{pmatrix}
, \tag{2.32}
\]

where the normalisation factor \( f_V \) is given by

\[
f_V = \sqrt[3]{\frac{a^2}{b c}} \tag{2.33}
\]

As shown in Eqn. (2.6), the formally expected relative height of a spherical distribution is dependent on the minimum and maximum radii. Therefore the random samples are set-up with the minimum and maximum radii as found for the Milky Way (see Table 2.1). For ellipsoidally distributed random samples the initial values are scaled such that the final distribution has the expected minimum and maximum radii.

As for the observed data, each random sample is bootstrapped 10 000 times and we calculate the shape parameter \( \gamma \) and the strength parameter \( \zeta \) of the resulting distribution of fitted normal vectors. Fig. 2.17 (central panel) shows a contour-plot \( \zeta \) vs. \( \gamma \) derived for 100 000 random samples from an isotropic distribution \( (a = b = c) \) each consisting of eleven model satellites, bootstrapped 10 000 times. As can be seen from the coloured regions, which show the density distribution, the distribution of normal vectors of bootstrapped random samples is not expected to be randomly distributed in \( (\gamma, \zeta) \)-space. They are typically found to be girdled or transitional \( (\gamma \lesssim 1) \) and marginally concentrated \( (\zeta < 3) \), while there is also some fraction of clustered \( (\gamma > 1) \) distributions. For oblate parent configurations (Fig. 2.17, upper panel) much more clustered distributions \( (\gamma > 1) \) result which are typically also more concentrated \( (\zeta \gtrsim 3) \). On the other hand, for prolate parent configurations (Fig. 2.17, bottom panel) typically a much higher fraction of girdled distributions \( (\gamma < 1) \) results, but also with higher concentration parameter \( (\zeta \gtrsim 3) \). Small concentration parameters are mostly found for an isotropic distribution.

To calculate the significance of an observed distribution, the joint distribution function \( D(\gamma, \zeta) \) is computed and the percentile of bootstrapped random samples is derived for
2.4 Statistical significance of disc-like distributions

Figure 2.17: A contour-plot of strength parameter $\zeta$ versus shape parameter $\gamma$ for 100,000 random samples, each consisting of eleven model satellites with an isotropic (central panel), oblate ($c/a = 0.5, b/a = 1.0$, top panel), and prolate ($c/a = b/a = 0.5$, bottom panel) parent distribution, each individually bootstrapped 10,000 times. The coloured contours show the density distribution of the derived parameters, dark red being high density. The contour lines show the enclosed values with significance levels as labelled. The star marks the parameters derived for the Milky Way.
which both the shape parameter and the strength parameter are larger than found for an observed satellite distribution, e.g. of the Milky Way (Fig. 2.17, solid contour lines). For each parameter pair of initial values \( c/a \) and \( b/a \) we create 100,000 random satellite samples each consisting of eleven satellites. Each of these samples is individually analysed using the bootstrap method with 10,000 re-samplings. This required a large amount of CPU time and we ran the simulation on the computer system of the Argelander-Institute and the CIP-pool\(^{(e)}\) of the physics department. The full run took about 7,500 CPU-hours running simultaneously on up to 30 PCs from 500 MHz class to 3 GHz class CPUs using a distributed computing technique.

2.4.1 The Milky Way

The percentile of models found to have bootstrapped distributions more concentrated than for the Milky Way are listed in Table 2.6. Approximate contour lines for a 1, 2, and 5 per cent probability that the Milky Way satellites (the classical data-set) are drawn randomly from a parent distribution with initial axis-ratios \( c/a \) and \( b/a \) are shown in Fig. 2.18. The values typically obtained for Milky Way sized dark matter haloes (see, e.g., Libeskind et al. 2005) are shown by the grey shaded region.

The same analysis for a sample of twelve satellites is repeated with 20,000 random samples, and the derived shape parameters are compared with those found for the Milky Way satellites including the UMa dwarf galaxy. The resulting fractions are listed in the bottom part of Table 2.6. Including the recently discovered dSph in Canes Venatici, we ran only one test with 13 satellites and 20,000 random samples for a spherical setup. For this run we find 0.3 per cent of the random samples more concentrated than for the Milky Way sample.

The null-hypothesis that the Milky Way satellites are drawn randomly from a spherical or mildly triaxial parent population as it is typically found in cosmological dark matter simulations can be excluded at very high statistical significance, \( \geq 99.5 \) per cent, confirming the results of Kroupa et al. (2005). With increasing triaxiality, the probability increases for more oblate configurations (which are marked with a grey background in Table 2.6). Prolate configurations are basically excluded, except for configurations nearly perfectly triaxial, e.g., for \( c/a = 0.5 \) and \( b/a = 0.7 \), where the probability may be of order 1 per cent. Including the UMa dwarf galaxy increases the significance of this result (reduces the probability).

2.4.2 Andromeda

For Andromeda, using an appropriate setup, the percentile values for the case that the satellite distribution within the approximate virial radius is drawn randomly from a spherically isotropic parent distribution is already 12 per cent for the KG-data. This reflects the fact that we find the bootstrapped normals of the M31 satellite system to be much less clustered than for the Milky Way. The distribution of bootstrapped normals for the M1 data-set are even less clustered and the percentile value is thus larger. So the hypothesis that the full

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2.4 Statistical significance of disc-like distributions

Table 2.6: Percentile of bootstrapped random samples for which the shape parameter and the strength parameter indicate a distribution of the normals of bootstrapped satellites more concentrated than found for the Milky Way satellite system. Different setup distributions are used with axis ratios \(c/a\) (along rows) and \(b/a\) (along columns). The top table gives the percentile for the innermost eleven satellites, the bottom table for the innermost twelve satellites including the UMa dwarf satellite candidate. Parameter combinations for which \(c/b < b/a\), i.e., which are triaxial and more oblate, are highlighted by a light grey background colour.

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<tr>
<th>(c/a)</th>
<th>0.3</th>
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M31 satellite system is drawn randomly from a spherically isotropic parent distribution can not be rejected at present, using the available data.

2.4.3 Statistical significance of M31 subsamples

Performing the analysis as described above for the morphologically (§2.3.1) and kinematically (§2.3.2) motivated subsamples would not yield the correct significance levels: the null-hypothesis for deriving the statistical significance is that all satellite galaxies within a certain radius trace a parent distribution, i.e., one assumes all satellite galaxies to be of the same origin, namely luminous DM sub-structures. But performing the analysis as above would imply that the eight satellites selected by the morphological or kinematical criterion are luminous dark matter sub-structures, randomly drawn, and the excluded ones are of another origin. Even in the case of the morphologically motivated subsample, where one may argue that all dSphs/dEs have been build due to the same mechanism, some were excluded because of their large distance from the fitted plane. But, they should have been included to derive the significance, because otherwise one implies a different origin of the excluded satellites. Koch & Grebel (2006) did not take this into account.

To derive the significance correctly, the procedure is to set up twelve model satellites
within the appropriate distance range from M31 and then select all combinations of eight model galaxies out of the full sample. For each of these individual subsamples, 495 in total, a full bootstrap analysis has to be performed. Then the fraction of random samples that have subsamples of eight model satellites with a more pronounced disc-like distribution than the observed sample needs to be calculated.

Practically, this analysis can only be performed for a few specific set-ups because the runs take a large amount of CPU time. We performed one run for each of the data-sets, MI and KG, respectively, using an isotropic parent distribution. The differences between both random runs are the minimum and maximum radii, chosen to match the values of the corresponding observed data-sets. We setup 10 000 random samples. The full run took about 20 000 CPU hours, running simultaneously on more than 30 standard PCs.

The percentile value for the case that the morphologically motivated subsample is picked from samples that are randomly drawn from an isotropic distribution is 100 per cent for the MI data-set and 95 per cent for the KG data-set. The percentile value for the kinematically motivated subsample is 17 per cent for the MI data-set and 10 per cent for the KG data-set. Even though appearing as a ‘thin’ disc-of-satellites, we conclude that the morphologically motivated subsample is just a chance alignment of galaxies and fully consistent with being randomly drawn from an isotropic distribution. For the kss8 subsample we can also not reject the hypothesis that the satellites are picked from a random sample, but the percentile value is much lower (< 17%) for both data-sets.
2.5 Discussion

The statistical methods to analyse the spatial distribution of the satellite galaxies of the Milky Way and Andromeda is not based on the “thickness” of a planar-like distribution alone, as this is not sufficient to characterise the distribution (Kang et al. 2005; Zentner et al. 2005). The bootstrap method is used to derive the distribution of poles of fitted planes which are analysed using methods based on the statistical analysis of spherical data. These methods quantify the robustness of a planar-like distribution. Thus, a population of satellites that is not planar-like will in our analysis be robustly identified as an unstable distribution of poles.

2.5.1 The Milky Way system

Applying two methods (ALS and ODR) to fit planes, the Milky Way satellite system within 254 kpc is found to be highly anisotropical. All “classical” companion galaxies are aligned in a disc-like structure with an rms-height of only $\Delta = 18.5$ kpc (Table 2.2). This disc-of-satellites is highly inclined with respect to the Milky Way’s stellar disc, $|b_{MW}| \approx 12^\circ$, passing the Galactic plane close to the Galactic Centre, $D_P \approx 8$ kpc $< \Delta$. The statistical methods, applied to the satellite system of the Milky Way, show that the hypothesis that the Milky Way satellites are drawn randomly from an isotropic distribution can be excluded at a high statistical significance level ($\geq 99.5$ per cent). It can also be excluded that the distribution is drawn randomly from a triaxial or prolate parent distribution as typically found in cosmological simulations of Milky Way sized haloes (e.g., Jing & Suto 2002; Bullock 2002; Libeskind et al. 2005; Zentner et al. 2005), Diemand et al. (2005a) specifically argued that the distribution of haloes formed early is even more elongated, i.e. more prolate than the smooth host dark matter halo. The null-hypothesis that the satellite system is drawn randomly from a dark matter parent distribution is therefore rejected only if the parent distribution is highly triaxial and oblate, i.e. if the parent distribution is already flattened. In this case, and as long as no host-galaxy formation is included in large scale CDM simulations, the disc of the Milky Way has to be postulated to be nearly perpendicularly oriented to the oblate host halo, because we find the disc-like structure of satellite galaxies to have a polar alignment. Even so, the required highly triaxial oblate DM-host shape is only marginally consistent with the results of modern CDM structure formation simulations. Furthermore, recent measurements of the shape of the Milky Way potential using the Sagittarius stream indicate it to be almost spherical within about 60 kpc (Fellhauer et al. 2006, see also §6.2).

The discoveries of two additional faint Milky Way companions that were included in the full analysis, increases the confidence in the above statements. Indeed, all the recently detected dSphs lie close to the DoS, except for the Hercules dwarf. It can not be excluded that the Hercules dwarf has been scattered into its current orbit (compare Sales et al. 2007a). However, since the SDSS (York et al. 2000) mostly covers the north pole region of the Galactic sky (Figs. 2.3 and 2.7) the detection is biased towards this region. But there are remarkably large portions of the sky that are way off the DoS – but no satellite galaxies are reported there. To get an answer beyond the possible sky-coverage bias it will be crucial to extend the search for Milky Way companions over a larger area of the sky and particularly at lower Galactic latitudes, as it is planned by the Stromlo Missing Satellite (SMS) survey (Jerjen et
Analysis of the spatial distribution of satellite galaxies

al., in preparation) using the new ANU SkyMapper telescope (Schmidt et al. 2005). We note though that if additional very faint dwarf galaxies are discovered to not lie within the disc-of-satellites as quantified here, as for example the Hercules dwarf appears to be (Table 2.1), we are nevertheless left with the fact that the eleven most luminous Milky Way satellite galaxies are aligned in the disc.

For the Milky Way a significant fraction of dwarf galaxies may be invisible in the optical due to obscuration by the Galactic disc at low Galactic latitudes (e.g., Mateo 1998). Within the virial radius of the Milky Way about half of the total volume has latitude $b \leq 30^\circ$. Andromeda is in that sense a better probe since it’s halo is not that much affected by obscuration (McConnachie & Irwin 2006b). A simple estimate for the Milky Way, assuming that all undetected satellites are homogeneously distributed over the whole sky, and further assuming that all satellites with $b \leq 15^\circ$ are undetected, 50 per cent of all satellites with $15^\circ < b \leq 30^\circ$ are undetected, we find that about 35 per cent of all satellites with $b \leq 30^\circ$ may be found more than $1\sigma = \Delta$ off, and about 30 per cent more than $3\sigma$ off the fitted disc-of-satellites. This is a very conservative estimate for the Milky Way obscuration. McConnachie & Irwin (2006b) estimated that only regions within $|b| < 15^\circ$ are affected by obscuration, and those with $|b| < 5^\circ$ to be the most strongly affected regions.

2.5.2 The Andromeda system

For the Andromeda satellite system it cannot be excluded that it has been drawn randomly from a spherical isotropic parent distribution. However, we do find the Andromeda satellite system to be anisotropic (left panels in Figures 2.10, 2.11, 2.15 & 2.16), but the details depend on the distance data used. The fitted disc-like structure for all satellites within the approximate virial radius is not as polar-aligned as for the Milky Way ($|b_{M31}| \approx 30^\circ$) and it is approximately twice as ‘thick’ as found for the Milky Way (Table 2.2).

Two incompatible subsamples of satellite galaxies which have a disc-like distribution can be identified: one morphologically motivated, as proposed by Koch & Grebel (2006), and one kinematically motivated (§2.3.2). Since the disc-like satellite system of the Milky Way is dominated by dSph galaxies, one can speculate about a common building mechanism for all the dSphs in the Local Group that is also the cause for a plane-like alignment of satellite galaxies. If this mechanism was the break-up of a large, gas-rich galaxy or the formation of tidal dwarf galaxies (TDGs) in an early major-merger event, one expects the dSphs to have initially correlated directions of their angular momentum vectors, supporting a disc-like structure. This would favour the morphologically motivated subsample since it is initially composed of dSphs only. However, at least two of the Andromeda dwarf spheroidals within the virial radius do not fit into this picture and were excluded by Koch & Grebel (2006) because of their apparently large distance from the plane. Also only one out of three morphologically similar dEs is found close to the disc. On the other hand we cannot exclude the possibility that some massive TDGs may retain their interstellar medium to appear today as dIrr galaxies (Hunter et al. 2000; Recchi et al. 2007).

The disc-like distribution of the morphologically motivated subsample of dSph/dE galaxies (mss8) around Andromeda is present for the KG data-set only, but cannot be identified for the MI data-set. Comparing the results of the AE and the bootstrap test it follows that even in the KG data-set the systematic errors caused by the distance uncertainties are
larger than the intrinsic scatter as quantified by the bootstrapping. Furthermore, the high significance of the morphologically motivated disc as derived by Koch & Grebel (2006) must be incorrect because of three reasons: firstly they derived their significance based on the thickness of the disc alone, secondly they used the ODR fitting method that is affected by the systematic alignments of the distance uncertainties of the M31 satellites, and thirdly, most importantly, they did not use the correct null-hypothesis to derive the significance. We find the distribution of the morphologically motivated subsample of Andromeda satellite galaxies to be fully consistent with being picked from a random distribution.

The kinematically motivated subsample of eight Andromeda satellites forms a pronounced thin disc with inclination of $\approx 31^\circ$ away from a polar alignment, and that holds true for both data-sets, MI and KG. The kss8 subsample is found to have a much more pronounced disc-like distribution than the morphologically motivated one, although its apparent thickness, as quantified by $\Delta$, is larger. Even though the kinematically motivated subsample has a much higher statistical significance than the morphologically motivated one, we can also not exclude the possibility that this sample is picked from a random distribution.

Interestingly, also all the newly discovered satellite galaxies of Andromeda lie close to its DoS as derived for the whole satellite population and the kinematically motivated subsample (Figs. 2.8, 2.9 and Figs. 2.15, 2.16). This is in particular remarkable given that the Andromeda system is much less affected by obscuration. Majewski et al. (2007) noted that along a radial vector from the centre of M31, connecting NGC 147 and And XIV, in total six satellite galaxies are located in projection, and Irwin et al. (2008) found that And XVII is also on that line. We demonstrated that the new dSphs lie on a straight line not only in projection, but taking their full 3D data into account, we find that they belong to the same disc-of-satellite as previously derived. This holds true despite large distance uncertainties.

2.5.3 The Milky Way versus Andromeda

There is no obvious evidence for a spatial association of the disc-of-satellites of the Milky Way and the Andromeda galaxy or its satellites (but see Sawa & Fujimoto 2005). If Andromeda, located at $b_{\text{MW}} = 121.7^\circ$, $b_{\text{MW}} = -21.5^\circ$, and its satellites were associated with the disc-of-satellites of the Milky Way, M31 ought to be close to the fitted disc-like structure, and the fitted planes ought to be aligned. Instead, M31 is $\approx 55^\circ$ off the fitted plane of the Milky Way satellites. Similarly, the angle between the normals of the fitted satellite planes of the MW and M31 is $\approx 50^\circ – 60^\circ$, but would be $0^\circ$ if they were perfectly aligned.

Fig. 2.19 shows the directions of the spin-poles (SP) of the stellar discs of the Milky Way and Andromeda in supergalactic coordinates (de Vaucouleurs et al. 1991), as well as the spin-poles of the smaller Local Group galaxies LMC and M33 (van der Marel & Cioni 2001; Corbelli & Schneider 1997). Additionally, the directions of the normals of the fitted disc-like structures of the satellite distributions of the MW and M31 are shown. It follows that the spin-axis of the Milky Way lies very close to the supergalactic plane, within about $6^\circ$, and the normal of the Milky Way DoS is likewise close to the supergalactic plane, but almost $90^\circ$ off the spin-axis of the Milky Way. The spin-axis of the stellar disc of Andromeda and the normal of its fitted DoS are both about $30^\circ$ off the supergalactic pole. If both discs-of-satellites were build up by the individual accretion of galaxies, preferentially from
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Figure 2.19: A Lambert projection – left for negative and right for positive latitudes – of the directions of the spin poles (SP) of the stellar discs of Milky Way and Andromeda in supergalactic coordinates, marked by filled circles, as well as of the smaller Local Group galaxies LMC and M33, marked by open circles. The directions of the normals of the fitted plane of all satellites of the MW and M31 within their virial radii are marked by squares and triangles, respectively (MI data: triangles pointing downwards, KG data: triangles pointing upwards). The dark square marks the direction of the normal of the Milky Way DoS that is its probable orbital pole as shown later in Section 3.2

the direction of the supergalactic plane, i.e. from the direction of the medium-scale (a few Mpc) matter distribution, then the normals of the discs-of-satellites should be close to the supergalactic pole. The orientation of the Milky Way DoS and the mutual miss-alignment of the discs-of-satellites contradict this notion.

The highly-inclined orientation of the stellar disc of the Milky Way relative to the supergalactic plane can be understood either as being a result of tidal torquing (Navarro et al. 2004) or resulting from the perpendicular collapse of matter onto the supergalactic plane (Doroshkevich 1973; see also Hu et al. 1998). If tidal torquing is responsible for the orientation of the Galactic disc, this begs the question as to why the other discs were not affected, and how tidal torquing affects the discs-of-satellites – one is highly inclined, the other is not. Alternatively, it would appear more natural or intuitive to understand a disc-of-satellites as being the result of stochastically occurring mergers which leave populations of related tidal dwarf galaxies. Such populations would remain visible for highly inclined events relative to the host discs, because populations of TDGs in low-inclination orbits would precess apart and possibly end up merging altogether with their host discs (Peñarrubia et al. 2002) or being more quickly destroyed than on polar orbits.

It appears implausible that for both systems the disc-of-satellites is present due to observational biases only. That would be a very strange coincidence. Rather, these findings strengthen the case that the discs-of-satellites for both, the Milky Way and Andromeda, are signs of a spatial correlation of the satellite galaxies.