Astron. Astrophys. 364, L97–L100 (2000)

ASTRONOMY
AND
ASTROPHYSICS

Letter to the Editor

Comments on the expected isotropic distribution curves in galaxy orientation studies

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Received 16 October 2000 / Accepted 16 November 2000

Abstract. We present results of random simulations for the expected isotropic distributions of the polar and azimuthal angles of galaxy rotation axes. It is found that selection effects concerning position and inclination of galaxies can remarkably change the shape of these distributions. Selection effects of this kind may play an important role when galaxies are taken from an incomplete dataset (e.g. from a limited region of the sky). These effects can lead to artificial structures (and hence to misinterpretations, as it already happened in the literature) and should be taken into account when deciding upon isotropy or anisotropy in the spatial distribution of spin vectors of galaxies. In this paper we discuss the various effects of selection.

Key words: galaxies: clusters: general – galaxies: general – galaxies: statistics – catalogs

1. Introduction

Investigating the distribution of spin vectors (SVs) of disk galaxies (with respect to a proper reference plane, e.g. the parent cluster plane) can be regarded as a clue to study and understand the process of formation of large scale structures: these SVs can be an indicator of the initial conditions when galaxies and clusters formed, provided the angular momenta of the galaxies have not been altered too much since their formation.

Contemporary theories advocate three different predictions concerning the spatial orientation of SVs of galaxies. First, the 'Pancake model' (see, e.g. Doroshkevich 1973, Doroshkevich & Shandarin 1978) predicts that the SVs of galaxies tend to lie within the cluster plane. Second, according to the 'Hierarchy model' (see, e.g. Peebles 1969) the directions of the SVs should be distributed randomly. Third, the 'primordial vorticity theory' (see, e.g. Ozernoy 1978) predicts that the SVs of galaxies are distributed primarily perpendicular to the cluster plane.

In most of the recently published papers on the origin of angular momenta of galaxies a 'position angle (PA) - inclination method' was used to study the spatial orientation of SVs of galaxies (e.g. Flin & Godłowski 1986, Kashikawa & Okamura 1992, Godłowski 1993, 1994, Hu et al. 1995, 1997, 1998, Yuan et al. 1997, Godłowski & Ostrowski 1999). This method was initially proposed by Jaaniste & Saar (1978) and later refined by Flin & Godłowski (1986). In this method, the measured PAs of galaxies (e.g. measured on photographic plates) are converted into 3-dimensional SVs using inclination angles which are obtained from the measured axial ratios. The distribution of these SVs can now be compared with a hypothesis, e.g. an isotropic spatial distribution.

In all previous work an underlying isotropic distribution of the SVs of galaxies in 3-dimensional space was assumed for analysis. This assumption leads to specific distributions of other parameters, e.g. the polar and azimuthal angles (see later), which we call the expected isotropic distribution curve for the parameter in question. Any deviation from this curve was in general considered as an indication of anisotropic distribution. However, the expected isotropic distribution curves could be seriously influenced by selection effects. So its nature should be examined for the various types of these effects.

2. The PA-inclination method

The 3-dimensional orientation of the SV of a galaxy is characterized by two angles: the polar angle θ between the galactic SV and a reference plane, and the azimuthal angle ϕ between the projection of the galactic SV on to this reference plane and the X-axis within this plane. When using the Local Supercluster (LSC) as reference, then θ and ϕ can be obtained from measurable quantities as follows (Flin & Godłowski 1986):

$$\sin\theta = -\cos i\,\sin B \pm \sin i\,\sin P\,\cos B \quad (1)$$

$$\sin\phi = (\cos\theta)^{-1}[-\cos i\,\cos B\,\sin L + \sin i(\mp \sin P\,\sin B\,\sin L \mp \cos P \cos L)] \quad (2)$$

where i is the inclination angle, estimated with Holmberg's (1946) formula: $\cos^2 i = [(b/a)^2 - (0.2^2]/(1-0.2^2)$ with b/a being the measured axial ratio. L, B and P represent the supergalactic longitude, latitude, and position angle, respectively.

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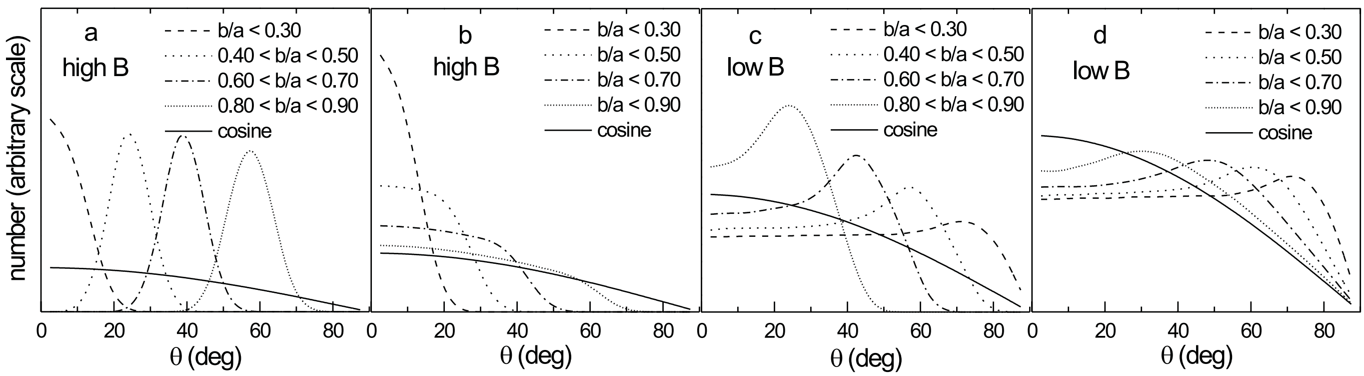

Fig. 1a–d. The expected isotropic distribution of the polar angle for different selections on inclination angle (a/b) and position. For the simulations we have used $-10^\circ \leq B \leq +10^\circ$ for 'low B' and $80^\circ \leq B \leq 90^\circ$ for 'high B'

Note, that for a given value of i, these expressions give two solutions for both θ and ϕ and hence 4 solutions for the angular momentum vector of the galaxy. However, for a large sample of galaxies it is hardly possible to determine - for each galaxy - which one is the physical correct one. As usual we have counted each of these possibilities independently.

Note further, that Eqs. (1) and (2) will give one single solution for both θ and ϕ when a galaxy is seen exactly face-on ($i = 0^\circ$). When seen edge-on ($i = 90^\circ$), the two solutions for both θ and ϕ differ just in sign.

More interestingly, the characteristics of the solutions for θ and ϕ are also strongly influenced by the used coordinate system. This was already noted by Flin & Godłowski 1986 (their Sect. 6.1). These authors suggested an analytical method to remove these selection effects due to positions. In the case of θ, both solutions converge when approaching the supergalactic pole or for galaxies with supergalactic PA $P = 0^\circ$. In the case of ϕ both solutions just differ in sign for $L = 0, \pi$. As an example, let a galaxy cluster of small angular size be filled with galaxies whose SVs are randomly distributed in space. The distribution of the calculated angles θ and ϕ will then depend on the position of that cluster on the celestial sphere. Consequently, when considering a larger region the expected distribution of θ and ϕ will be defined by the location of that region on the sky, but also by its boundaries.

Mathematically, the expected distribution of the calculated values of θ and ϕ, when applying the expressions (1) and (2), is determined by the assumed spatial distribution of the SVs of the galaxies and the interval from which the variables L, B, P, and i have been taken. The latter influence is what we call selection effect in the following.

Due to the special form of the expressions (1) and (2) these selection effects cannot in general be calculated analytically. In order to minimize the selection effects due to positions and inclination angles we have done numerical simulations.

3. Results

The true spatial distribution of the SVs of galaxies we have assumed to be isotropical. Then, due to projection effects, i can be distributed $\propto \sin i$, B can be distributed $\propto \cos B$, the variables L and P can be distributed randomly, and formulae (1) and (2) can be used to calculate the corresponding values of θ and ϕ. Our results are based on calculations including $2 \cdot 10^5$ virtual galaxies.

3.1. Selection effects and the isotropic polar angle distribution

In Fig. 1 we demonstrate that selection effects either concerning inclination and position will change the expected isotropic polar angle distribution dramatically. Consider first what happens with this distribution when selecting different inclinations. When all possible inclinations are included in the measurements, the isotropic distribution of θ is $\propto$ cosine. It is this curve which was already used previously as the isotropic distribution for the polar angle by different authors. However, all the other curves in Fig. 1 show selection effects at work. When face-on galaxies are missing, this curve is deformed significantly. However, this deformation is dependent on the supergalactic latitude of the galaxy sample (this effect was already noted by Godłowski 1993). When this sample is located at high B, a 'hump' develops at small values of θ and a long range 'dip' at large angles when neglecting face-on galaxies more and more (see Fig. 1 b). These effects work the other way round when the region in question is located at low supergalactic latitudes (Fig. 1 d): a 'hump' develops at large values of θ and a 'dip' at small values. It should be noted here, that we call here and in the following 'dip' and 'hump' (under apostrophes) deviations relative to a reference curve (here cosine).

To study these effects in more detail, Fig. 1 a and c gives the constituents of these cumulative effects. It is shown how the isotropic polar angle distribution changes and deviates from $\propto$ cosine for a sequence of galaxies from nearly face-on to nearly edge-on. Let us begin the discussion for low values of B (Fig. 1 c, d) for nearly face-on galaxies ($0.80 \leq b/a < 0.90$) a 'hump' at small angles and a 'dip' at large angles is found. As the number of face-on galaxies is reduced from the sample, the reverse pattern is achieved: a 'dip' at small angles and a 'hump' at large angles for nearly edge-on galaxies. When going to higher supergalactic latidudes, all these individual isotropic distribution curves will become narrower and shifted. Note, that

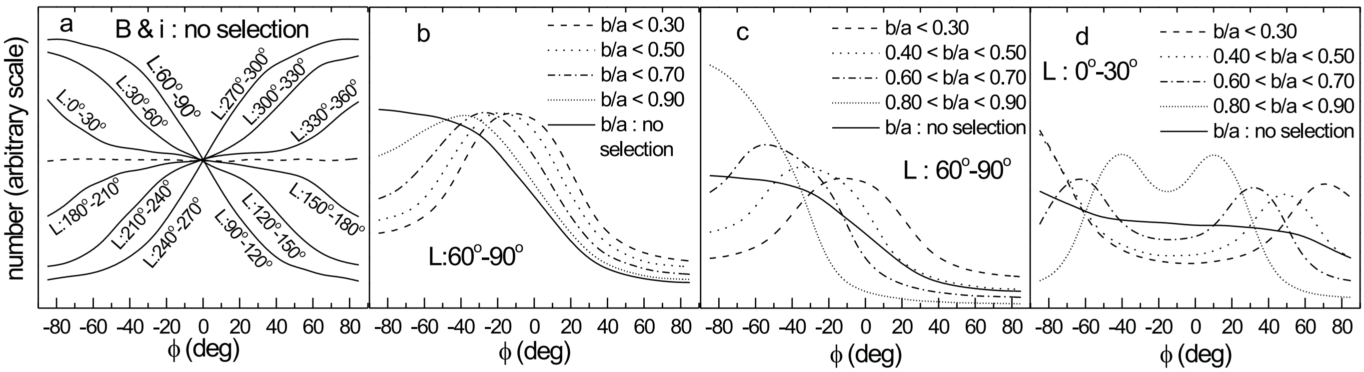

Fig. 2a–d. The expected isotropic distribution of the azimuthal angle for different supergalactic longitudes and inclinations

distribution curves which peaked at high values of θ for low B are shifted to low values of θ when increasing B, and vice versa.

Fig. 1 makes clear that the expected isotropic θ-distributions of edge-on galaxies and pole-on galaxies are very different due to selection effects. Maybe this effect can play a role, at least in part, in results already published. In this way the correct treatment of face-on galaxies is a crucial point. Artificial structures will play an important role because PAs for nearly face-on galaxies cannot be measured with proper accurancy (in particular when measured visually).

3.2. Selection effects and the isotropic azimuthal angle distribution

To study these effects we have first devided the whole sky into 12 parts having $\Delta L = 30°$ with no selections on B and i. Fig. 2 a shows in which way the isotropic azimuthal angle distribution changes due to selection effects concerning L. It can be seen that the position of galaxies (i.e. the region investigated) has marked influence upon the expected isotropic distribution of ϕ. We found a wavelike structure: a 'dip' ('hump') at $90°$ and a 'hump' ('dip') at $-90°$ for galaxies with $L < 180°$ ($L > 180°$, resp.). These artificial structures are more pronounced when L is approaching $90°$ ($270°$, resp.). So the nature of the isotropic distribution curve for the azimuthal angle is different for northern and southern hemisphere galaxies. However, this effect could be removed by using the (analytical) method of Flin & Godłowski 1986 (see Flin & Godłowski 1990), because there is no selection on i.

Fig. 2 b, c, d demonstrate how selection on the inclination will change the isotropic distribution for $L \approx$ constant. As an example, in Fig. 2 b and c we show the case for $60° \leq L \leq 90°$. It can be seen that for edge-on galaxies there is a 'dip' at negative regions of ϕ and a 'hump' at the other side. When going to face-on galaxies the maxima of the distribution curves is shifted to negative values of ϕ. For face-on galaxies this trend is opposite.

Moreover, the influence of this selection is dependent also on the choice of L, as is shown in Fig. 2 d, where we have put our results for $0° \leq L \leq 30°$. The isotropic distribution now is different from that of the above choice of L and more complex.

In addition, selection effects of B will make the shape of the expected isotropic distribution in Fig. 2 b, c and d even more complex.

Up to now, no authors have used homogeneous data covering both the northern and southern hemisphere for their investigations on SVs of galaxies. Flin & Godłowski (1986) mainly used UGC galaxies. Later Godłowski (1993, 1994) added galaxies taken from the ESO B Atlas. Kashikawa & Okamura (1992), Yuan et al. (1997), and Hu et al. (1998) used the Photometric Atlas of Northern Bright Galaxies (Kodaira et al. 1990, hereafter PANBG) and investigated galaxies with $\delta > -25°$.

3.3. Applications

To show that these artefacts from selection effects can play an important role in interpreting data we give some examples from the literature. Hu et al. (1998) and Yuan et al. (1997) have used the PANBG as data base for their studies. Because they have used only northern galaxies, we can expect isotropic azimuthal distributions similar to those in Fig. 2. Indeed, in their histograms of azimuthal angle distributions, these authors found a remarkable dip at $-90°$ to $-50°$ and a hump at $40°$ to $60°$ which could be mainly due to the positions of their galaxy samples. In addition, if we make a closer look on the histograms of azimuthal angle distribution of Kashikawa & Okamura (1992), Hu et al. (1995, 1997), a similar trend in all histograms of ϕ distribution for their subsamples can be seen. This trend can be due to the inhomogenous distribution of their galaxies.

From Fig. 2 (subset 3b S(VI)) of Hu et al. (1995) we have taken data points and error bars directly from the published figure. To calculate the expected isotropic polar angle distribution for the database which was used by these authors we have taken the region $12^{\rm h}04^{\rm m} < \alpha < 13^{\rm h}03^{\rm m}$ and $-3°47' < \delta < 21°44'$ for the Virgo cluster region and distributed the inclination angles within the intervall $25° - 90°$.

The result is given in Fig. 3 a. The authors noticed a dip at small θ due to missing face-on galaxies and corrected it roughly by distributing galaxies randomly in this range. However, after this correction an anisotropic feature at $\theta < 10°$ still remains, according to the authors. However, accepting our ex-

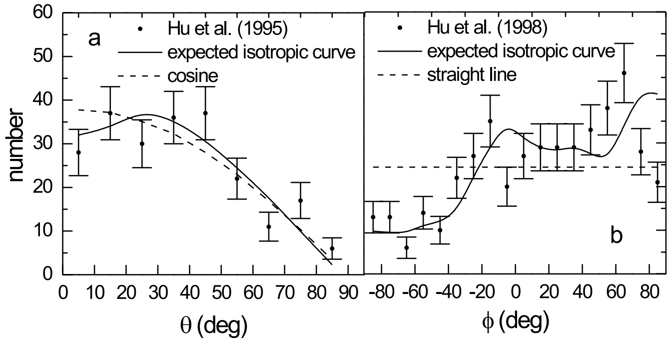

Fig. 3a and b. a The data are taken from Fig. 2 of Hu et al. 1995. The solid line is the isotropic distribution of the polar angle. **b** The data are taken from Fig. 7 of Hu et al. 1998. The solid line is the isotropic distribution of the azimuthal angle

pected isotropic distribution, also this feature is just an artefact due to selection effects.

A further example is shown in Fig. 3 b. These data were taken from Fig. 7 of Hu et al. (1998). Similar data can be found in Yuan et al. (1997). To calculate the expected isotropic distribution of ϕ we have used exactly those regions which were treated in that article. No selection were made on inclination, because the PAs were measured by fitting a 25 mag arcsec^{-2} isophote level. This example clearly demonstrates the need of considering selection effects in investigations of SVs of galaxies. The global shape of the measurements can be fitted with the expected isotropic distribution.

4. Conclusions

It is shown that any selection criteria imposed on the datasets may cause severe changes of the nature of the expected isotropic curve. We found that the isotropic distribution curve remains cosine for the polar angle and a straight line for the azimuthal angle (as previously adopted) only when there is no selection on B, L, P and i. The analytical method of Flin & Godłowski 1986 can be used only, when there are no selections on i. However, in all available databases both the positional and inclination effect are present. So simulations should be performed. In the following we summarize how selection effects will change the shape of the isotropic distributions:

1. The isotropic polar angle distribution is independent of L but changes with B when making selections on i.
2. The isotropic distribution for the polar angle is independent of B and L only when the range of i is full (i.e. no selections made); this distribution is independent of i, if there are no selections on positions.
3. The azimuthal angle distribution is independent of the range of B, provided the range of i and L is full. It changes with L even when the range of i and B is full.
4. The isotropic polar angle distribution is different for edge-on and face-on galaxies when making selections on B. However, the isotropic azimuthal angle distribution remains unchanged for face-on and edge-on galaxies when the range of L is full.

Acknowledgements. We thank the referee, Dr. W. Godłowski, for his comments which have improved this paper significantly. B. Aryal acknowledges the *Österr. Akad. Austauschdienst (ÖAD)*, Austria, for providing scholarship and Tribhuvan University, Kathmandu, Nepal, for the study leave.

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