Inferring Galaxy Viewing Angles

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November 27, 1995

Abstract

The kinematic structure of remnants produced from major mergers of disk progenitors is examined. In particular, we consider moments of the projected velocity field and quantify departures of the line profiles from gaussianity using a Gauss-Hermite expansion. By averaging over circular apertures, we are able to show that the line profiles exhibit significant deviations from gaussianity and, of greater interest, we find that the high-order moments correlate with viewing angle. This effect appears to be a natural consequence of the orbital structure of equilibrium triaxial systems.

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The correlations in our models appear sufficiently tight that it may be possible, in principle, to infer viewing angles from observations, provided that the kinematics of the remnants in our simulations are representative of those of actual elliptical galaxies. Observational tests of our scheme are proposed, and possible applications of the technique to the study of intrinsic properties of galaxies and clusters are discussed.

Keywords: Galaxies — Kinematics and Dynamics : Galaxies –Structure : Galaxies – Elliptical and Lenticular, Cd

1 Introduction

The structure and dynamics of collisionless stellar systems are determined by their properties in a six-dimensional phase space. Unfortunately, observations provide direct information on only three of these coordinates: two projected spatial dimensions and one line-of-sight velocity. Deducing the intrinsic nature of astronomical objects from this incomplete description is a daunting task. In principle, considerable progress can be made in the case of galaxies whose light profiles are relatively smooth and when it can be assumed that their internal structure is relatively simple. In that event, the three-dimensional shape of a galaxy, for example, can be inferred from the projected morphology, if the viewing angles are known.

For galaxies having rotating disks, like spirals, the usual procedure is to assume that the disks are axisymmetric and thin. The projection angle relative to the rotation axis then follows immediately knowing the projected ellipticity of the disk. However, this approach can fail when the assumptions noted above are violated; in particular, for galaxies having large-amplitude spiral arms, bars, or non-circular disks. In fact, whether spiral disks are indeed circular is a point of contention. Franx and de Zeeuw (1992) argue that galactic disks are nearly round while other studies point toward asymmetries in spiral disks (Rix and Zaritsky 1995), which would complicate attempts to derive viewing angles for spirals.

More problematic are systems having fewer obvious symmetries, such as ellipticals. A variety of methods have been used to derive viewing angles for early-type galaxies, but these schemes are generally limited to special cases or are statistical in nature. For example, the presence of a gas disk or dust lane can sometimes be used to constrain the orientation of spheroidal systems relative to the line of sight (e.g., Lees 1991; Quillen *et al.* 1992). This technique suffers from many of the same limitations as in the case of spirals and is further complicated by any triaxiality of the potential. More significant, most ellipticals lack strong dust lanes and gas disks. Benacchio & Galletta (1980) and Galletta (1980) have used observed correlations between isophotal twists and apparent ellipticity to constrain shapes, but this approach is model dependent.

Binney (1985) showed that a statistical analysis of minor axis rotation can be used to determine the distribution of intrinsic shapes of ellipticals. Franx, Illingworth and de Zeeuw (1991) have applied this technique to existing data, but, of course, it cannot be used to infer the shapes of individual objects. de Zeeuw and Franx (1991) review the efforts to determine the intrinsic shapes of elliptical galaxies and to understand their kinematics in detail. Recently, Statler & Fry (1994) suggested that detailed modeling of the velocity field can be used to determine the three-dimensional structure of individual ellipticals. Statler (1994) applied this technique to NGC 3379. The approach assumes that the velocity and density field can be well-approximated by separable functions of radius and angle, an assumption that may be violated in real galaxies.

Here, we describe an alternate scheme that may well be more general than those reported earlier. The basic idea behind our method is to make use of kinematic data, parameterized by moments of the line-of- sight velocity distribution. Our technique draws upon earlier attempts by others to construct detailed models of nearby galaxies (Franx & Illingworth 1988; Bender 1990; Rix & White 1992; van der Marel & Franx 1993; Kuijken & Merrifield 1993; Gerhard 1993; Dehnen & Gerhard 1993; van der Marel et al. 1994a; van der Marel et al. 1994b). Rather than relying on radial profiles of high-order moments, however, we employ an aperture synthesis approach and find that averages computed in this manner correlate well with viewing angle for triaxial systems. In principle, this result makes it possible to constrain the viewing angles of individual elliptical galaxies and bulges by observations of their line profiles. The nature of these correlations can be understood qualitatively by appealing to the following simple examples. In an oblate system, stars move only on short-axis tube orbits. When stars (or gas) on these orbits in a thin stellar disk are viewed in an aperture that is centered on an edge-on galaxy, the resulting line profiles are double-peaked and highly non-Gaussian. On the other hand, when an oblate system is viewed along the minor axis (face-on), the line profile is more nearly Gaussian. Dehnen and Gerhard (1994) have verified this argument using analytic, two-integral models for oblate elliptical galaxies. Variations in the structure of velocity profiles can be used to constrain the angle between the line-of-sight and the minor axis in oblate galaxies.

In a triaxial system, stars can move along short-axis tube orbits, box orbits, and long-axis tubes. Box orbits fill pinched rectangular volumes whose long axes lie along the major axis of the potential. Consequently, when box orbits are viewed from a point along the major axis, their velocity distribution is broad since they project a large velocity component along the line of sight. However, when such orbits are viewed along either the intermediate or minor axis, their contribution to the velocity distribution is peaked since their line of sight component is small. Thus, as we show in §2, if most stars in an elliptical galaxy are on either box or short-axis tubes, we expect measurements of the shapes of line profiles to constrain the viewing angles. The correlation we have just described would be degraded to some extent by stars on long-axis tube orbits. However, both numerical simulations of elliptical galaxy formation (Barnes 1992; Heyl et al. 1994a) and the observed alignment between kinematic and photometric axes in ellipticals (Franx, Illingworth & de Zeeuw 1991) suggest that the structure of real ellipticals is probably not dominated by long-axis tube orbits.

To make these arguments firmer, we use numerical simulations of the formation of elliptical galaxies by major mergers to quantify the non- Gaussian nature of projected line profiles in remnants of these events. Results of these calculations and the correlations we find between high- order moments of the velocity field and the viewing angles are presented in §3. We propose observational tests of our technique in §4, where we also discuss potential applications of the approach to both galaxies and clusters of galaxies. Conclusions are given in §5.

2 Viewing angles and kinematics

In the past several years, several researchers have recognized the possibility that detailed studies of line profiles can yield new insights into the structure of galaxies. By convention, the shapes of line profiles are quantified by moments of the velocity field. Through advances in detector technology, it has become possible to obtain not just the mean velocity and velocity dispersion from spectral observations, but third (skewness) and fourth (kurtosis) order moments as well.

Gerhard (1993) and van der Marel & Franx (1993) have pioneered the use of Gauss-Hermite expansions to extract these higher-order moments from the spectral data. Represented in this form, the higher-order moments are less sensitive to noise in the tails of the line profiles than, for example, the more familiar skewness and kurtosis. Measurements of Gauss-Hermite moments have already helped to constrain models of galactic nuclei (van der Marel et al. 1994a, 1994b). To the best of our knowledge, however, no one has attempted to use these quantities to infer viewing angles of galaxies.

For spherical systems, there is considerable freedom in constructing self-consistent models. Determinations of velocity moments can constrain the orbital distribution of spherical models (Gerhard 1993; van der Marel & Franx 1993). In triaxial systems, there is less freedom in how orbital families can be populated to generate fully self-consistent models. This is particularly true if the fraction of stars on long-axis tube orbits is small and most stars are on box orbits (Schwarzschild 1982; Statler 1987). As we argued in §1, when observed parallel to the major axis, a triaxial galaxy composed mainly of box and short-axis tubes will exhibit a broad range of velocities and have a velocity profile that is flatter than a Gaussian, and hence have a negative kurtosis. However, when viewed perpendicular to the major axis, these orbits contribute relatively smaller velocity components to the line profiles, and hence the velocity distribution is expected to be peaked near zero and have positive kurtosis. Thus, observations of line profiles in elliptical galaxies can potentially provide insight into their orientation and structure.

In order to explore these possibilities in depth, we have analyzed the projected velocity fields of merger remnants formed in computer simulations (Hernquist 1992, 1993a; Hernquist *et al.* 1993a, 1993b; Heyl *et al.* 1994b). Below, we illustrate the results of our analysis using two remnants each of which resulted from the merger of a pair of disk galaxies containing massive bulges. These remnants were chosen because of their morphological similarity to elliptical galaxies. Remnants produced by mergers of bulgeless stellar progenitors are not sufficiently concentrated to be identified with real ellipticals (Hernquist 1992, 1993b; Hernquist *et al.* 1993b).

The simulations analyzed here each employed 294,912 particles, evenly divided between the two progenitors. Details of the numerical technique and galaxy models have been reported previously (Hernquist 1993c). The two remnant galaxies discussed below were formed from an encounter (Remnant A) in which both disks suffered an exact prograde collision, and another (Remnant B) in which both disks were initially tilted with respect to the orbit plane (see Hernquist 1993a). The contrasting origins of the two remnants results in contrasting shapes. Remnant A has axis ratios 2.4:2.1:1 (E5-E6) while remnant B is more nearly spherical with ratios 1.6:1.4:1 (E3-E4). Neither remnant has significant figure rotation.

Of course, what follows could also be derived from self-consistent triaxial models. In the absence of analytic models having realistic orbital structure and density profiles similar to actual ellipticals, we decided to use the simulated merger remnants as examples of what might be expected in more general circumstances and because of their morphological and kinematic similarity to real galaxies. In particular, orbital analyses of remnants produced by major mergers suggest that the merger process populates all orbital families, and the major-axis tubes are not strongly represented (Barnes 1992; Heyl *et al.* 1994a) as in elliptical galaxies (Franx, Illingworth & de Zeeuw 1991). Thus, we have every reason to believe that our model galaxies do not represent perverse distribution functions, but are rather typical of actual galaxies.

We found it expedient to measure moments of the projected velocity field by computing the Gauss-Hermite moments within circular apertures centered on the luminosity peak of the remnant. Our conclusions depend only rather weakly on the size of the aperture; unless stated otherwise, the following results are for apertures with a radius equal to half the effective radius of the remnant (in projection). We "observe" each remnant from numerous viewing angles and measure the velocity moments from the different directions.

While the implementations of the Gauss-Hermite method suggested by Gerhard (1993) and van der Marel & Franx (1993) are more or less equivalent, we found it most convenient for comparison with observations to employ van der Marel & Franx's approach. For each viewing angle, we determine the projected half-mass radius, r_e, of the remnant, and calculate the moments,

$$s_l = \frac{1}{N}\beta_l \sum_{j=1}^{N} H_l(w_j) e^{-\frac{1}{2}w_j^2}, \tag{1}$$

where the sum is performed over the N particles within the aperture of $0.5r_e$, and $w_j \equiv (v_j - V)/\mu$. Here, V is the central velocity of the expansion, and μ is the scale. The normalization factor β_l is given by

$$\beta_l = \sqrt{\frac{1}{2^{l-1} l!}}. \tag{2}$$

The Hermite polynomials, H_l, are defined in the usual manner (Gerhard 1993) and successively higher values of l probe successively wider features of the velocity distribution. Here we calculate the moments to ninth order, although we will only discuss the fourth and sixth-order moments in detail. What remains is to select the central velocity and the scale for the expansion. The mean and the standard deviation of the velocity distribution are the obvious choices; however, these statistics depend strongly on the particles in the wings of the velocity distribution which are difficult to measure observationally.

So following van der Marel *et al.* (1994a), we select V and μ such that the first and second-order Gauss-Hermite moments are zero; that is,

$$s_1 = \frac{1}{N}\sum_{j=1}^{N} w_j e^{-\frac{1}{2}w_j^2} = 0 \tag{3}$$

$$s_2 = \frac{1}{2N}\sum_{j=1}^{N}(4w_j^2 - 2)e^{-\frac{1}{2}w_j^2} = 0. \tag{4}$$

Finding solutions for V and μ is straightforward by beginning with the measured mean and standard deviation (σ) of the distribution and iterating,

$$V_{n+1} = V_n + s_1\mu_n \tag{5}$$

$$\mu_{n+1} = \mu_n + s_2\mu_n. \tag{6}$$

It requires about five iterations through Equations 3 to 6 until s_1 and s_2 are less than 10^{-6}.

Once V and μ are determined in this manner, these values are used to compute the higher moments s_3 to s_9 as well as s_0. We then divide all of the moments by s_0, effectively renormalizing the distribution, such that $(s_0, s_1, s_2) = (1, 0, 0)$. Hereafter we use h instead of s to indicate that we are using the specific expansion in which the V and μ have been selected to zero the first two moments (*i.e.* the van der Marel & Franx formulation) and s_0 is one. In the limit of noiseless data, this moment calculation and the χ^2 fitting of van der Marel *et al.* will give the same values (van der Marel *et al.* 1994a). We choose the moment method because it is simpler to implement for N-body simulations and avoids binning the data which could lead to systematic errors. A positive value of an even moment of a Gauss-Hermite expansion will yield a kurtosis greater than three (using the convention that the kurtosis of a Gaussian is three).

Figures 1a and 1b show values of the velocity moment, h_4 over a sphere of viewpoints for the two simulations. In these plots, the minor axis runs through the "North" and "South" poles, and the major axis intersects the "equator" at from longitude 0^o and longitude 180^o. In spite of the differences between the two remnants (A is E5 and B is E3), h_4 reaches a minimum of approximately -0.15 when either remnant is viewed along the major axis and a maximum of about 0.06 when viewed along the minor axis. The intermediate axis at longitudes 90^o and 270^o along the equator is a saddle point.

Figures 2a and 2b are analogous to Figures 1, but depict the moment h_6. Again we see the h_6 correlates well with viewpoint; however, as it measures a

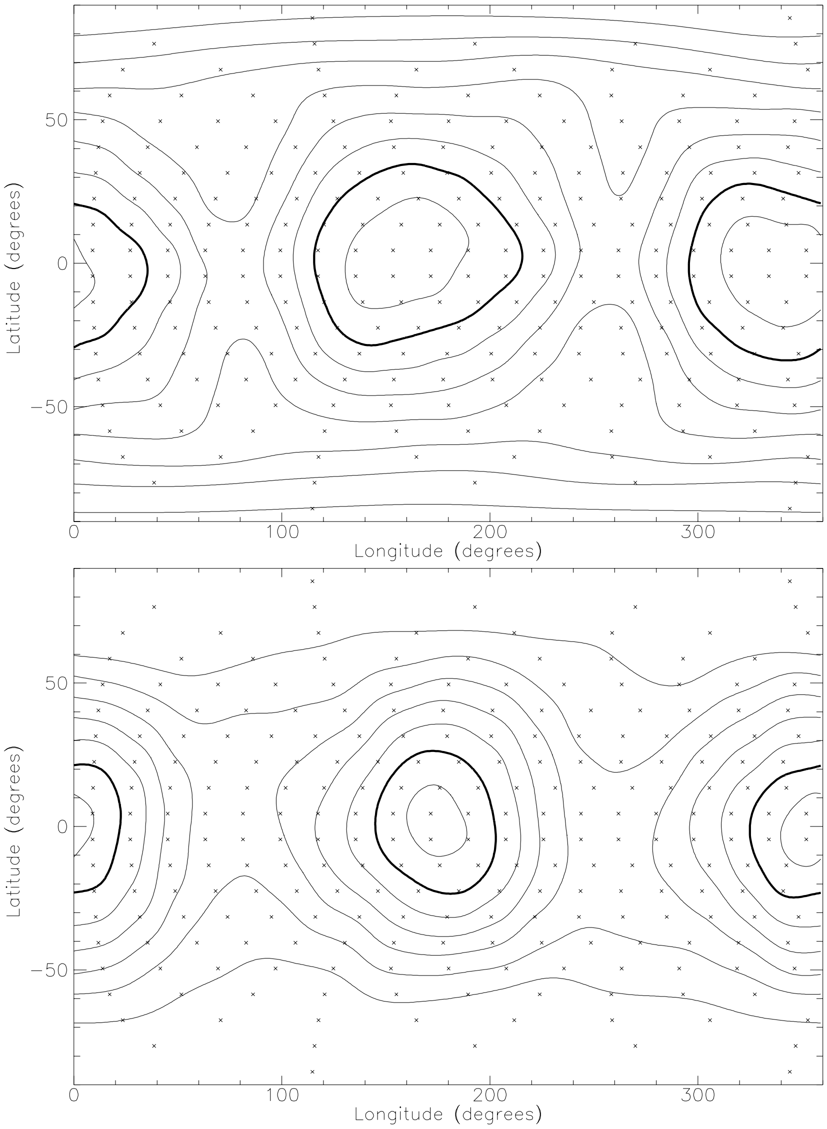

Figure 1: Figures 1a and 1b depict the dependence of h_4 on viewpoint for remnants A and B respectively. The viewpoints were evenly distributed over a sphere. In this plot, the minor axis passes through latitude $\pm 90^o$, the poles, and the major axis runs through the equator at longitudes 0^o and 180^o. The contours have values separated by 0.01. The dark contour is at $h_4 = 0$ and the contour within it traces the locus $h_4 = -0.01$. The crosses are where h_4 was measured.

higher order deviation of the velocity distribution from gaussianity, the map is more noisy. Additionally, the structure is different for the two models. In both remnants h_6 reaches a clear maximum at the intermediate axis and a minimum at the minor axis; however, remnant B has a mininum in h_6 along the major axis and remnant A has a saddle point of some sort. The successively higher moments reveal exhibit finer structures; however, they are more noisy. On the other hand, the odd moments do not correlate well with viewing angle; however, statistically they reveal information about the progenitors of the remnant and the collision (Heyl *et. al.* 1994a).

Having fixed the overall velocity normalization of a triaxial galaxy from its velocity dispersion, it may then be possible to use measurements of these higher order moments to infer the orientation of the galaxy in three dimensions. For example a measurement that $h_4 = 0.03$ within an aperature of $0.5 r_e$ would imply that our line of sight is nearly parallel with the intermediate axis of the galaxy. A measurement of the higher moments (such as h_6), although more prone to error, could further constrain the galaxy's orientation and provide a consistency check.

It will be interesting to compute these various quantities from other galaxy models to see if the correlations found here persist in other situations.

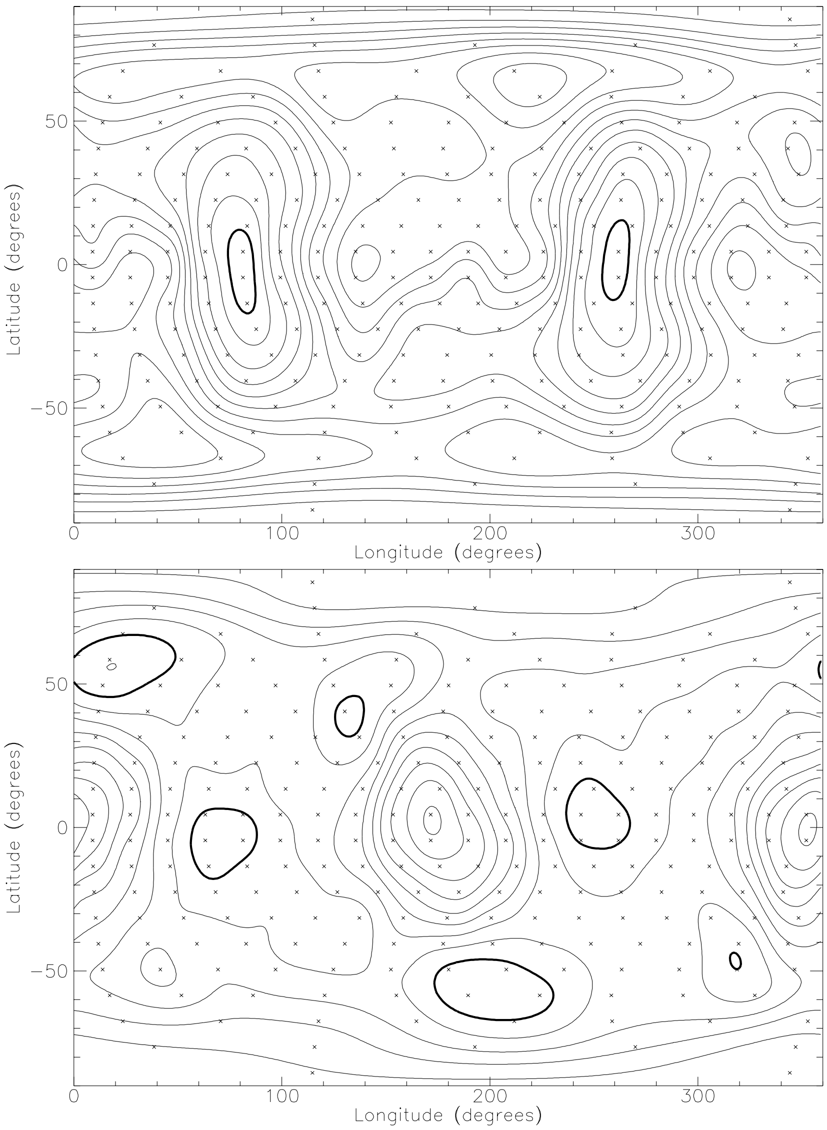

Figure 2: Figures 2a and 2b depict the dependence of h_6 on viewpoint for remnants A and B respectively. The coordinate system is identical to those of Figure 1. The contours have values separated by 0.002. Here, the dark contour is at $h_6 = -0.02$, and the contour values decrease outside this contour. The crosses are where h_6 was measured.

In fact, we have every reason to believe that our results are not peculiar to the models we have analyzed, but are a natural consequence of the equilibrium structure of triaxial systems. Through further analysis we determined that the correlations seen in Figures 1–2 apply even when the aperture is sufficiently large to cover the entire remnant, in projection.

3 Observational tests and applications

While analyses like that presented here can establish plausible correlations between galaxy viewing angle and velocity moments, observational tests will be needed to confirm this effect in real galaxies. Early type spirals are an excellent laboratory for testing our predictions. It would be interesting to determine if the inclination angle inferred from the stellar or gaseous disk of an Sa or S0 galaxy agrees with that obtained by measuring velocity moments of its bulge.

If the correlations are confirmed, then bulge kinematics will provide an alternate approach for inferring the orientations of disk galaxies. It should then be possible to use this information to reduce the scatter in the Tully-Fisher relation. In addition, inclinations of spirals could be estimated independently of any assumptions regarding the intrinsic shapes of disks or even for galaxies having large amplitude spirals or bars.

Polar ring galaxies provide an opportunity for directly testing our ideas in the case of elliptical and S0 galaxies. Models of these systems predict the orientation of these galaxies on the sky from the shapes of polar rings (see, *e.g.* Whitmore *et al.* 1987; Sackett & Sparke 1990). The viewing angles so determined can be compared with those inferred from our analysis. Polar ring galaxies may be preferable to ellipticals with strong dust lanes for testing our predictions, as dust lane absorption in the centers of the ellipticals complicate the observation of kinematics of these systems.

An accurate determination of the intrinsic shapes of early-type galaxies would enhance our understanding of the structure and evolution of these objects. The $D_n - \sigma$ relation likely has at least a weak dependence on galaxy orientation. Clearly, it would be intriguing to look for correlations between velocity moments and deviations from the $D_n - \sigma$ plane, to eliminate scatter in these observed quantities. A more accurate measurement of the statistical distribution of the intrinsic shapes of ellipticals promises to place significant constraints on models for the formation of these galaxies (*e.g.* de Zeeuw & Franx 1991; Dubinski & Carlberg 1991; Hernquist *et al.* 1993a).

Our results may also be useful for studying clusters of galaxies. Real clusters are expected to be somewhat triaxial and, at least in cases where they are relaxed, should display correlations similar to those in elliptical galaxies. Dutta (1993) has calculated velocity moments for galaxies in his cluster simulations; it will be interesting to see if they correlate with viewing angle. If so, observations of high-order velocity moments of clusters (Zabludoff, Franx & Geller 1993) should constrain their orientation. This information will be particularly useful in clusters for which the Sunyaev-Zel'dovich effect is used to measure the Hubble constant. Observations of prolate clusters viewed edge-on underestimate the Hubble constant, while oblate clusters lead to the opposite effect.

4 Discussion

We have proposed a new technique for inferring viewing angles of hot stellar systems. Detailed observations of line profiles in the centers of elliptical galaxies and bulges can constrain their projected orientation. Elliptical galaxies viewed along their short axes are expected to have peaked velocity profiles (positive kurtosis), while those viewed along their long axes should have broad line profiles (negative kurtosis).

We have quantified this expected correlation between viewing angle and kinematics by "observing" elliptical galaxies produced by N-body simulations of the merger of pairs spiral galaxies containing bulges and halos. We computed the velocity moments using a Gauss-Hermite expansion (Gerhard 1993; van der Marel & Franx 1993) and found that h_4 and h_6 correlate well with orientation. This tightness of the correlation in our simulations suggests that observations of velocity moments may make it possible to infer galaxy orientations to an accuracy of $\approx 10 - 15^o$.

We expect this correlation to be reasonably robust. While it is possible to construct equilibrium models in which the effect is degraded, *i.e.* when long-axis tube orbits are heavily populated, it seems unlikely that most stars in real galaxies are on these orbits, as suggested by computer simulations of galaxies formed by mergers of dissipationless collapse and because the kinematic and photometric axes in ellipticals appear to be well-aligned (Franx, Illingworth and de Zeeuw 1991).

Future observations of bulges in early-type spirals and of polar ring galaxies could confirm the correlations seen in our numerical experiments. If our predictions are verified, the use of high order velocity moments promises to be a powerful tool for studying the internal structure of early-type galaxies.

Acknowledgments

This work was supported in part by the Pittsburgh Supercomputing Center, the Alfred P. Sloan Foundation, NASA Theory Grants NAGW- -2422 and NAGW–2448, and the NSF under Grants AST 90–18526, AST 91-17388, ASC 93-18185, AST 88-58145 (PYI), and the Presidential Faculty Fellows Program. This work was completed as part of J.S.H.'s senior thesis and was supported by the Roundtable Senior Thesis Fund. J.S.H. also received support from the Marshall Aid Commemoration Commission. J.S.H. and D.N.S. would also like to thank the members of the department of Astronomy and Astrophysics of the University of California – Santa Cruz for their hospitality during preparation of this work.

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