DYNAMICS OF THE GALACTIC SPHEROID

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ABSTRACT. The intrinsic shape and the kinematics of the Galactic bulge and the metal–poor stellar halo are discussed. There is strong evidence that the Galactic bulge is triaxial, and is rotating rapidly. The stellar halo is nearly round, rotates slowly, and has an anisotropic velocity distribution.

1. Introduction

The Galactic bulge and the metal–poor stellar halo are the two major constituents of the Galactic spheroid (Freeman 1987). A careful study of their photometric, kinematic and dynamical properties is required to answer questions such as: What kind of spiral galaxy do we live in? Can we think of the bulge as a small elliptical galaxy? What is the shape and extent of the dark halo? How was the Galaxy formed? An extensive and up–to–date discussion of these and related issues can be found in Freeman (1987), and in the Proceedings of the 1989 Saas Fee Advanced Course on *The Milky Way as a Galaxy* (Gilmore, King & van der Kruit 1990). In this review we concentrate on two specific questions that have received considerable attention in the past few years, namely, i) what is the intrinsic shape of each of the two components of the spheroid, and ii) what is their internal velocity structure?

2. The Galactic Bulge

2.1. INTEGRATED LIGHT

The Galactic bulge is heavily obscured at optical wavelengths, and is best studied in the near–infrared. Early measurements showed that the integrated surface brightness distribution between 2 and 2.4 micron is flattened, and has a central cusp (Becklin & Neugebauer 1968; Maihara *et al.* 1978; Matsumoto *et al.* 1982; Allen, Hyland & Jones 1983). A variety of functions have been proposed as fits to the observed surface brightness profile, including power laws, exponentials and de Vaucouleurs' profiles. Sellwood & Sanders (1988) reviewed much of the early work, and showed that the volume emissivity profile in the inner 500 parsec is well–described by a power–law with slope –1.8, while at larger radii the profile steepens considerably, and the slope approaches –3.7. Kent (1992) analyzed the Spacelab 2.4 micron data (Kent, Dame & Fazio 1991) and corrects for foreground contamination by the disk, which may amount to 40% of the observed light. The resulting bulge profile is similar to the

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one proposed by Sellwood & Sanders, and has a characteristic major axis scale–length of about 900 pc. The bulge isophotes have an axis ratio of 0.61, and are slightly box–shaped. Inside one kpc the bulge may be more flattened.

Blitz & Spergel (1991b) have reanalyzed the balloon measurements of Matsumoto *et al.* (1982), and find that the bulge is in fact brighter on one side than on the other. They argue that this is not due to extinction variations, but is caused by the bulge being triaxial rather than oblate, with the near side at positive galactic longitude. Their analysis does not constrain the axis ratio of the bulge in the plane of the disk, nor does it give an accurate value for the angle ϕ between the long axis of the bulge and the line–of–sight to the Galactic center. Analysis of the COBE map of the Galaxy might improve this situation.

2.2. GAS KINEMATICS

It has been known for a long time that the inner rotation curve of the Galaxy displays a prominent hump. If ascribed to circular motion, it requires a very strong central density concentration (Bahcall, Schmidt & Soneira 1982). A more natural explanation is to assume that the central part of the Galaxy is not axisymmetric, but contains a triaxial bulge. The simple closed orbits available to the gas are now elongated, and the gas velocity varies along the orbit. When viewed from the proper direction, i.e., by proper orientation of the bulge, one may therefore observe gas velocities that are substantially higher than the local circular velocity, and hence see a hump in the rotation curve (e.g., Lake & Norman 1983). Gerhard & Vietri (1986) showed that the inner rotation curve can indeed be reproduced in this manner, for example by a prolate bulge with a stationary figure, seen nearly broadside on. Evidence for non–circular motions in the central regions of the Galaxy had been discussed earlier by Liszt & Burton (1980) in terms of a simple kinematic model which is in fact equivalent to motion on elliptic orbits (see Kent 1992).

Binney *et al.* (1991) have constructed the most comprehensive model to date of the motions of both the atomic and the molecular gas in the inner kpc of the Galaxy. These authors assume the gas moves on non–selfintersecting closed orbits, and show that a rapidly rotating inner bar with its corotation radius at 2.4 ± 0.5 kpc, an axis ratio in the plane of the Galaxy of 0.75, and seen nearly end–on at an angle ϕ to the line–of–sight equal to $16° \pm 2°$, provides a natural explanation for the observed kinematics of the gas. Designating the elongated central component as a bar or as a triaxial bulge may be a matter of semantics: the gas motions in the Galactic plane do not constrain the density distribution of the bar outside the plane, and, as Binney *et al.* point out, it is possible that the rapidly rotating bar is identical to the triaxial box–shaped bulge evident in the integrated light (§2.1). The bar and the bulge may also be separate Galactic components: an initially flat bar in a disk galaxy may grow fatter in time, become box–shaped, and either form a bulge, or a metal–rich component in a pre–existing bulge (Combes *et al.* 1990; Pfenniger & Norman 1990). Thus, the bulge and/or the bar may have formed separately from the halo.

Proper treatment of the gas kinematics probably requires use of a two–dimensional hydrodynamical code, because the closed orbit approximation breaks down when the orbits become very elongated, or when the gas switches from one orbit family to another. Early hydrodynamical studies that discuss the effects of a triaxial bulge on the Galactic HI kinematics include van Albada (1985) and Mulder & Liem (1986). The former author requires a bar which is rather similar to the one found by Binney *et al.* (1991), wheareas the latter authors require a bar which has its nearest side at negative rather than at positive longitude. Both studies use a rather crude approximation to the Galactic potential. It clearly is worthwhile to redo this kind of study, but now with a more up–to–date potential.

Much of the classical work on stars in the bulge has been restricted to a small number of special areas that are not heavily obscured by interstellar extinction, and hence gives only limited information on the shape and structure of the entire bulge (e.g., Frogel 1988). The IRAS mission has improved this situation dramatically. Habing *et al.* (1985) showed that a simple criterion based on the observed flux densities at 12 and 25 micron allows one to select evolved stars located near the tip of the AGB from the IRAS point source catalog. The resulting distribution of sources on the sky clearly shows the disk of the Galaxy, and the bulge (see also Habing 1988). The inferred luminosity profile (corrected for the effects of confusion near the Galactic plane) is consistent with that deduced from the integrated light measurements, and the measured axis ratio is about 0.7 (Harmon & Gilmore 1988).

The recent interest in triaxiality has spurred re-analysis of the properties of various populations of bulge stars. Nakada *et al.* (1991) investigated the luminosity function of a subsample of the IRAS AGB stars in the bulge, and found that the stars at positive longitudes are brighter on average than those at negative longitudes. Whitelock & Catchpole (1992) similarly find that the bulge Mira variables at positive longitudes have a mean distance smaller than those at negative longitudes, just as expected. The RR Lyrae stars show marginal evidence for a triaxial distribution also, but with its near end at negative longitude (Wesselink 1987; Le Poole & Habing 1990). It will be interesting to see whether this result holds up when a larger sample is studied, since unlike the Miras and the AGB stars, the RR Lyraes presumably belong to the metal-poor halo. This may itself be triaxial, and indeed elongated in a direction opposite to the bulge (Blitz & Spergel 1991a; §3.1).

Weinberg (1992) has re-analyzed the IRAS point source catalog, considered only objects with galactic latitude $|b| < 3°$, and used selection criteria based on the IRAS colors which differ slightly from those employed by Habing *et al.* (1985). He assumes that all these stars have the same absolute bolometric luminosity, calculates individual bolometric corrections based on the observed IRAS colors and some assumptions about the spectral energy distribution, and furthermore assumes a uniform extinction throughout the Galaxy. This yields distances for all the objects, and results in a map of AGB stars in the Galaxy. The distribution is not axisymmetric, but appears to be lopsided. Weinberg argues that this is due to the apparent luminosity cutoff of his sample, which means that hardly any stars beyond 10 kpc are included. Analysis of a deeper, but incomplete, sample shows a more symmetric bar-like distortion, again with the near side at positive longitudes. Instead of fitting a specific model to the distribution of stars, Weinberg calculates the coefficients of the harmonic expansion that fits the data best. He reconstructs a smooth density distribution from his expansion coefficients, ignoring the asymmetric terms. This yields a symmetric bar, out to about 5 kpc, with the near side at positive longitude, an axis ratio in the plane of the Galaxy of about 0.6, and seen at an angle ϕ of 36°. Varying the prescriptions for the bolometric correction and for the extinction, and allowing for a spread in intrinsic luminosities of the AGB stars, does not change the main result—the existence of a bar—but does influence its properties. Specifically, the viewing angle ϕ may well be somewhat smaller, meaning the bar is seen more end-on, in agreement with the rotating bar of Binney *et al.* (1991). It remains to be seen whether the spatial extent of 5 kpc found by Weinberg can be reconciled with the much smaller size found by Binney *et al.* It is also not clear to what extent confusion of sources in the Galactic plane influences this result.

Weinberg's analysis is restricted to the Galactic plane. It should be extended to three dimensions as soon as larger samples of stars in the bulge are available. The proposed 2MASS (Kleinmann 1991) and DENIS (Epchtein & Burton 1992) sky surveys at 2 micron will see every AGB star in the Galaxy, and are the ideal datasets for doing this problem.

Stars at the tip of the AGB are surrounded by an expanding dust shell, and can be readily identified by means of their OH emission at 18 cm. The spherical geometry of the shell causes the line profiles to be double–peaked, so the measured velocity width is twice the expansion velocity of the shell, and the mean velocity is the radial velocity of the embedded star. Because radio measurements are not hampered by Galactic obscuration, these OH/IR stars may well be the best set of tracers to study the kinematics of the entire bulge.

Early radio surveys of the inner bulge (Habing *et al.* 1983; Winnberg *et al.* 1985) found a few dozen OH/IR stars, and showed that the bulge may well rotate rapidly, with rotation velocities of about 100 km/s at less than 100 pc from the center, and with a radial velocity dispersion between 60 and 140 km/s. Lindqvist *et al.* (1991) have recently completed a large VLA survey, and now have 134 OH/IR stars in the central 100 pc. The earlier fast rotation is confirmed, and the dispersion about the mean motion is found to be of the order of 80 km/s (Habing *priv. comm.*). This value for the dispersion is lower than the 110 km/s for the giants in Baade's window (Sharples, Walker & Cropper 1990; Tyson & Rich 1990), but compares well with that derived for Mira variables (Catchpole 1990, Menzies 1990) and planetary nebulae (Kinman, Feast & Lasker 1988), which are in evolutionary stages bracketing the OH/IR stage. Both the Miras and the planetary nebulae show evidence for rotation, but these populations reach rotational velocities of 80 km/s only at about 750 pc from the Galactic Center. This appears to differ from the fast rotation of the OH/IR stars, but may be due to the customary but suspect fitting of linear rotation curves to samples that go out to different distances from the center. It is also possible that the OH/IR sample includes a population of disk objects. The rotation of the Miras and the planetary nebulae is consistent with the figure rotation expected for the bar invoked by Binney *et al.* (1991) to explain the gas kinematics in the inner kpc.

A number of OH 18 cm surveys of IRAS point sources have been carried out (Eder, Lewis & Terzian 1988; te Lintel–Hekkert *et al.* 1989; Sivagnanam *et al.* 1990), resulting in radial velocities for about 1500 OH/IR stars in the Galaxy. This sample is incomplete near the Galactic plane. Te Lintel–Hekkert & Dejonghe (see te Lintel–Hekkert 1990) have modeled the observed kinematics by choosing a potential for the Galaxy, and then asking what intrinsic velocity distribution is consistent with the observed kinematics. So far, they have considered oblate models in which the velocity dispersion is isotropic in the meridional plane. They find evidence for two components in their models, and identify one with the old disk, and the other with a "thick disk plus bulge". Although the sampling of the bulge is incomplete, the models give mean streaming motions (rotation) of about 100 km/s at 1 kpc, and a velocity dispersion of well over 100 km/s.

The method used by te Lintel–Hekkert & Dejonghe is quite flexible. Radial velocities from different samples—notably the Lindqvist *et al.* (1991) data—can be included, provided the selection effects are understood. The effects of an anisotropic velocity distribution can be incorporated easily, and may be tested by use of proper motion surveys such as done in Baade's window (Spaenhauer, Jones & Whitford 1992). Models with a stationary triaxial bulge can be considered also, but inclusion of figure rotation will require a considerable numerical effort. Ideally, one would like to take the mass model of Binney *et al.* (1991) and then investigate whether the radial velocities of different populations are consistent with each other, or whether they indicate truly different Galactic components (see Rich 1990). This should also settle the issue of whether the bulge formed directly by gaseous infall from the halo, or is an inward extension of the (thick) disk (see e.g., Lewis & Freeman 1989; Carney, Latham & Laird 1990). Such a project is feasible, and would be helped considerably by a complete radio survey of the OH/IR stars in the bulge.

2.5. OTHER BULGES

Various lines of evidence suggest that spiral bulges as a class are not oblate. The position angles of the apparent major axis of the bulge and the disk of spiral galaxies often differ from each other. This is a natural consequence of triaxiality, and is caused by a projection effect. A well-known example is the bulge of M31 (Stark 1977). Bertola, Vietri & Zeilinger (1991) studied a sample of 32 bulges, and showed that if disks are round, then bulges as a class are indeed triaxial, and have shapes similar to elliptical galaxies. The derived distribution of shapes may be incorrect, however, as it is now clear that photometrically the disks of spirals are not round, but instead are slightly elongated, with an axis ratio close to 0.9. This issue was reviewed recently by Kuijken & Tremaine (1991; see also Franx & de Zeeuw 1992). Derivation of the intrinsic shapes of bulges will require inclusion of kinematic data, just as was done for ellipticals (Binney 1985; Franx, Illingworth & de Zeeuw 1991).

Stellar absorption line measurements of spiral bulges are consistent with rotationally supported axisymmetric models, when the disk potential is taken into account (Jarvis & Freeman 1985; Kent 1989). However, the data are consistent also with triaxial shapes with substantial internal streaming, and/or figure rotation. Individual bulges also show signs of triaxiality. The regular gas velocity field of NGC 4845 is well-fit by motion on elongated closed orbits in a triaxial bulge, with axis ratios $b/a = 0.74 \pm 0.06$ and $c/a = 0.60 \pm 0.06$ (Bertola, Rubin & Zeilinger 1989; Gerhard, Vietri & Kent 1989). The various recent indications that the Galaxy contains a triaxial bulge are therefore fully in line with what we know about other spiral bulges.

3. The Metal–Poor Halo

3.1. STARCOUNTS

The Galactic stellar halo consists of metal–poor stars, with [Fe/H] $\lesssim -1.0$. Starcounts have shown that the density profile of the stellar halo is proportional to $r^{-3\,5}$ out to about 20 kpc, and is possibly steeper beyond this distance (e.g., Saha 1985). The flattening of the halo deduced from starcounts is modest, with an axis ratio c/a between 0.6 and 0.8 (Gilmore, Wyse & Kuijken 1989).

Blitz & Spergel (1991a) suggested that many of the asymmetries in the Galactic HI velocity field can be explained by assuming that the spheroid is triaxial, and has a slowly rotating figure. The inferred axis ratio b/a in the plane of the disk is larger than 0.87, and the near side is at negative longitudes, with the long axis at roughly 45° from the line–of–sight to the Galactic center. This spheroid is therefore distinct from the central triaxial bar which is aligned in the opposite direction (§2). On the other hand, Kuijken (1991) has argued convincingly that a model in which the Galaxy is slightly lopsided, and has a round central bulge, gives at least as good a description of the HI velocities (see Kuijken & Tremaine 1991). It will be interesting to see whether detailed starcounts in a number of well–chosen directions will be able to confirm or rule out either of these suggestions.

3.2. STELLAR KINEMATICS

Ratnatunga & Freeman (1985, 1989) showed that the velocity dispersion of K giants in the direction of the South Galactic Pole remains constant out to large distances. This is a surprising result. In the solar neighbourhood the observed line–of–sight velocity dispersion comes from the motion perpendicular to the Galactic plane. As the distance above the

Galactic plane increases, the radial motion contributes more and more to the observed velocity dispersion. Since there is no reason to assume that the velocity dispersions in the radial direction and the direction perpendicular to the Galactic plane are equal—they differ in the solar neighborhood—one expects the observed velocity dispersion to vary. Not surprisingly, a model with constant anisotropy and a velocity ellipsoid aligned with spherical coordinates is inconsistent with the data. Ratnatunga & Freeman concluded that a constant anisotropy model can give a good fit to the data, but only if the velocity ellipsoid is aligned with cylindrical coordinates. This would imply that the halo is very flat, with $c/a < 0.5$, i.e., much flatter than deduced from starcounts (see also Binney, May & Ostriker 1987).

The value of c/a deduced from kinematic observations has gone up in the past few years, mainly due to corrections to the measurements. Morrison, Flynn & Freeman (1990) now take the local dispersion in the perpendicular direction to be 100 km/s, and argue that the lower value of 75 km/s used earlier was caused by inclusion of thick disk stars. Van der Marel (1991) has used the Jeans equations, considers both cylindrical and spherical alignment of the velocity ellipsoid, and assumes that the velocity anisotropy of the halo does not vary much with position. He finds that the starcounts and the kinematic data are consistent if the dark halo, which provides the gravitational potential, has $c/a > 0.34$. If the stellar and the dark halo have the same shape the constraint is $c/a > 0.53$.

A number of authors have constructed detailed dynamical models for the metal–poor halo based on phase–space distribution functions (White 1985; Sommer–Larsen 1987; Levison & Richstone 1986; Dejonghe & de Zeeuw 1988; Sommer–Larsen & Christensen 1989; Arnold 1990; Vedel & Sommer–Larsen 1990). Both spherical and oblate axisymmetric models with anisotropic velocity distributions have been considered, and they have been compared with kinematic data along a number of directions out of the Galactic plane. The best fitting models have a halo velocity distribution which is roughly isotropic in the central regions, somewhat radially anisotropic between 6 and 10 kpc, and tangentially anisotropic beyond 10 kpc. The evidence for tangential anisotropy at very large radii (~60 kpc) is less convincing (Arnold 1991; Norris & Hawkins 1991). The halo density distribution in these models has two components, one nearly spherical, with $c/a \gtrsim 0.7$, and the other more flattened, with a scale–height of less than 3 kpc. The distribution of RR Lyrae stars also shows evidence for two such halo components (Hartwick 1987).

Instead of measuring radial velocities for stars at large distances in the halo, one can also do a more comprehensive study of the metal–poor stars in the solar vicinity, by measuring not only their radial velocities but also their proper motions. The resulting space motions can be used to calculate the associated stellar orbits in a plausible Galactic potential. The fraction of its orbit that each star spends in the solar neighbourhood is then known, so that the observed number density of halo stars can be corrected to yield the total density distribution of all halo stars represented by the sample observed near the Sun. This approach was advocated by May & Binney (1986), and is sometimes referred to as doing halo observations from an armchair. It has recently been implemented by Sommer–Larsen & Zhen (1990). These authors use a separable Galactic potential, so that three integrals of motion are known analytically, and computation of the orbits and the correction factors is straightforward. They find that the stars that pass through the solar neighbourhood are representative of about 90% of the known halo population between 8 and 20 kpc, that these indeed have the $r^{-3.5}$ density law derived from direct starcounts, and that they can be divided into two components, one nearly spherical with $c/a \sim 0.85$ and the other substantially flattened, and possibly with a higher mean metallicity. The velocity anisotropy is found to vary with radius. These results agree remarkably well with the earlier studies using more distant samples. It will be interesting to include other local samples in this analysis (e.g., Sandage & Fouts 1987; Norris & Ryan 1989; Nissen & Schuster 1991).

The metal–poor halo rotates rather slowly, with $v_{\rm rot} \leq 40$ km/s (Norris 1986). This is indicated also by the kinematics of globular clusters. Whereas the disk globular clusters (with [Fe/H]> -0.8) form a reasonably fast rotating dynamical subsystem, the halo globular clusters (with [Fe/H]< -0.8) show almost no evidence for rotation (Zinn 1985; Armandroff 1989). This is consistent with a nearly spherical rotationally supported halo, but is equally consistent with a triaxial halo that is pressure supported, and has a nearly stationary figure (see also Long, Ostriker & Aguilar 1991).

If the stellar halo is triaxial, then the lack of figure rotation means that one can construct extensions of the available oblate dynamical models by using a separable triaxial potential for the Galaxy. The tools for doing this are available (e.g., Dejonghe & Laurent 1991). Such a modeling effort must be supported by additional kinematic data. The most recent dynamical models for the stellar halo are constrained by radial velocity measurements in a modest number of directions, and in some of these by data in only one or two distance bins (e.g., Arnold 1990; Vedel & Sommer–Larsen 1990). A major improvement in this situation will come from the inclusion of proper motion measurements for distant objects, such as carried out by Majewski (1991) and others. The triaxial models may also shed light on Majewski's suggestion that the stellar halo appears to be counter–rotating.

It is not evident that the customary procedure of first binning the kinematic data and then comparing the resulting averages with dynamical models is the best approach. There have been persistent suggestions that there is velocity clumping in the halo (e.g., Doinidis & Beers 1989), possibly due to the fact that small stellar groups drizzle in from larger radii, and leave their kinematic signature on the observed halo populations (Freeman 1987). Although some theoretical work has been done on this issue (Quinn & Goodman 1986), there is room for further careful N–body simulations, and also for an investigation of the consequences of velocity clumping on kinematic studies of the halo, and the associated dynamical modeling with smooth distributions.

3.3 OTHER GALAXIES

The properties of the Galactic metal–poor halo are consistent with what we know about the stellar halos of nearby normal galaxies. The metal poor globular clusters in M31 form a slowly rotating nearly round system (Elson & Walterbos 1988). The globular cluster systems of nearby elliptical galaxies are also nearly round and show marginal evidence for rotation (Mould *et al.* 1990). Radial velocity measurements of planetary nebulae in the halos of nearby galaxies promise to improve our knowledge of the velocity distribution in these systems substantially (Ford *et al.* 1989).

The dark halos of spiral galaxies, which dominate their gravitational potential, are likely to be triaxial. This is suggested by numerical simulations of galaxy formation (Frenk *et al.* 1988; White & Ostriker 1990; Dubinski & Carlberg 1991), which invariably result in prolate/triaxial dark halos. Luminous elliptical galaxies are triaxial as a class, but the majority of them is oblate/triaxial (Franx, Illingworth & de Zeeuw 1991). This may indicate limitations in the numerical simulations, but may also be caused, for example, by the effects of dissipation during the formation of the luminous part of a galaxy. By analogy, one expects that the stellar halos of spiral galaxies are triaxial, but that the dark halo simulations may be a poor guide to their shape. It is unlikely that we will be able to establish the triaxiality of nearby stellar halos directly any time soon, although misalignments between the kinematic and photometric axes of, e.g., the planetary nebula systems would be a strong indication. Spiral disks which are embedded in a triaxial halo are slightly elongated. Better constraints on the shapes of the dark halos therefore come from a careful analysis of the photometry and kinematics of the disks (see Franx & de Zeeuw 1992).

4. Conclusions

Observations of the integrated light, starcounts, and measurements of the kinematics of the atomic and molecular gas in the inner region of the Galaxy all indicate that the Galactic bulge is triaxial, with its near side at positive longitude, and its long axis close to the line–of–sight to the Galactic center. The COBE observations, and the starcounts to be done with the proposed 2 micron surveys, will further delineate the shape and orientation of the bulge. The consequences of triaxiality for the stellar kinematics of the bulge have not been explored yet, mainly because at present velocities are available for a relatively modest number of bulge stars. A systematic survey of OH/IR stars in the entire bulge will improve this situation dramatically.

Starcounts indicate that the metal–poor halo is slightly flattened, and has an axis ratio of about 0.8. Despite earlier reports to the contrary, the measurements of radial velocities in a number of directions out of the Galactic plane are consistent with a nearly round stellar halo, in which the velocity anisotropy varies with radius. Further improvements in the dynamical models for the halo are possible, notably inclusion of the effects of triaxiality, but they will require a substantial observational effort, including starcounts, radial velocity measurements, and proper motion studies. It is not clear whether the halo population is dynamically well–mixed. This issue needs urgent attention.

When combined with abundance measurements, kinematic studies will provide significant constraints on the formation history of the various components of the Galactic spheroid.

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Discussion

Ostriker: If the bulge is triaxial then low angular momentum orbits will be box like and at some point pass close to the Galactic Center. This destroys globular clusters in the inner few kiloparsecs with box–like orbits and then the survivors will be, as observed, a relatively rapidly rotating population (i.e., on tube orbits).

de Zeeuw: Agreed.