SUMMARY: ACHIEVEMENTS AND OPEN QUESTIONS

K.C. FREEMAN
Mount Stromlo and Siding Spring Observatories
Weston Creek PO, ACT 2611, Australia

1. Introduction

Without attempting to cover all of the topics discussed at this meeting, I plan to talk briefly about some of the major achievements and ideas that came up here, and then mention a few of the important open questions and some work that might be done to answer them.

2. Kent's Model

A good galactic model for the inner Galaxy is needed to interpret the kinematics and light distribution of various populations. Kent's (1992) simple model, based on the Spacelab 2.4μ surface photometry, has a radial density distribution $\rho(r) \propto r^{-1.8}$ for $r < 900$ pc and steepens to $\rho(r) \propto r^{-3.7}$ for larger r. The model is axisymmetric, isotropic and flattened, with axial ratio 0.6 and mass-to-light ratio $M/L(2.2\mu) = 1$, and it accounts nicely for the kinematics of a wide range of bulge tracers (OH/IR stars, K giants, the integrated bulge light, planetary nebulae and M giants) between about 1 and 1500 pc from the galactic center.

The model shows that the high apparent rotational velocities observed for HI and CO within about 1 kpc of the galactic center are unlikely to represent the true circular velocity in this region (as most people have long suspected anyway). Detailed analysis of gas motions in the inner few hundred parsecs indicates that there is a central bar, with pattern speed $\Omega_p = 63$ km s^{-1} kpc^{-1} (Gerhard). Corotation is at 2.4 kpc from the center, and the inferred density distribution is in excellent agreement with Kent's model. There is now much direct evidence for the presence of a central bar, from the distributions of several different bulge tracers (but not from the distribution of the RR Lyrae stars). Analysis of the COBE data should help define the parameters of this bar (de Zeeuw).

The true radial density distribution of the bulge is difficult to establish directly, because it is inevitably confused with gradients in the abundance and age of the stellar population (King, Rich). Kent's model is derived from infrared surface photometry and agrees well with the radial density distribution of Miras (Whitelock). However the other M giants and RR Lyrae stars in the inner bulge show a steeper radial gradient.

H. Dejonghe and H. J. Habing (eds.), Galactic Bulges, 263–269.

3. Kinematics of OH/IR Sources and SiO Masers

The (longitude, velocity) distributions are similar for the various kinds of bulge objects in late stages of stellar evolution (planetary nebulae, Miras, OH/IR stars, SiO masers), and there seems to be agreement that at least a fair fraction of these objects are very old (ages > 10 Gyr). The typical mean rotation of the bulge is about 10 km s^{-1} $degree^{-1}$. The kinematics of the SiO masers and OH/IR sources indicate that the velocity dispersion and mean rotation of the bulge decrease slowly with increasing galactic latitude for $|b| > 3°$. The velocity dispersion is $101 - 3.6\,|b|$ km s^{-1}, and the mean angular velocity is $15.6 - 1.23\,|b|$ km s^{-1} $degree^{-1}$ (Izumiura), so the rotation of the galactic bulge may be somewhat different from the cylindrical behaviour seen in the rotation of other boxy bulges.

Habing and Dejonghe presented a two-integral quadratic programming model to represent the distribution and kinematics of the OH/IR stars. The model gives the distribution of stellar orbits in the (angular momentum, energy) plane. The morphology of the model in this plane is interesting: qualitatively, it is like the two-integral distribution function models that have been constructed for boxy bulges (eg Rowley, 1988). For the future, the two-integral distribution function could also be derived for the inner bulge by applying Hunter's (1992) new inversion technique to Kent's model (de Zeeuw), and it will be interesting to see how well these two approaches agree.

The kinematics of the inner OH/IR stars (Lindqvist *et al*) show that the mean velocity reaches about 150 km s^{-1} at radius $R = 0°.5$. This velocity is close to the circular velocity for the Kent model, and suggests the presence of an inner disk which may be somewhat younger (Whitford). The brightest bulge objects at the K-band, which would include the youngest and most metal-rich, show the most flattening.

For the future, we look forward to the new VLA / Australia Telescope survey of the bulge OH/IR stars, and offer every encouragement for proper motion studies of the SiO and OH masers.

4. The bulge - halo transition

As King pointed out in his opening talk, we do not yet know how the galactic bulge is related to the other components of the Galaxy (thin disk, thick disk, halo). Many authors in the past have regarded the bulge and the metal-poor halo as together making up the galactic spheroid. However, in a late type galaxy like ours, the concept of the spheroid is itself not well defined (eg Wyse and Gilmore, 1988), and King suggests that this terminology should be avoided. Some results presented at this meeting indicate that the metal-poor halo and the bulge are probably not closely related.

The second parameter effect on the morphology of the horizontal branch, as seen in the halo globular clusters, is also shown by the blue horizontal branch stars (BHB) of the metal-poor halo. The ratio of RR Lyrae stars to BHB stars increases with increasing galactocentric distance, from the edge of the bulge ($l = 0^\circ$, $b = -10^\circ$) out to about 25 kpc from the center , and the BHB becomes less blue (Preston). For the globular clusters, the second parameter effect is now believed to be due to age variations with galactocentric radius: the outer metal-poor halo formed later and over a longer period of time.

In Baade's window, the horizontal branch is predominantly red. There appears to be a marked transition in HB morphology between halo and bulge, from the very blue HB just outside the bulge (ie inner halo) to the relatively red HB in Baade's window (ie bulge). Lee (1992) proposed that the RR Lyrae stars in Baade's window may be the oldest objects in the Galaxy. Renzini argued on other grounds that bulges are on average older than the metal-poor halos.

Preston estimated that the mass of the metal-poor halo stars ([Fe/H] < -1) within 1 kpc of the galactic center is about $3.10^8\ M_\odot$; this is only a few percent of the mass of the bulge. Morrison and Harding studied the stellar population in a bulge field at $l = -10^\circ$, $b = -10^\circ$. In this field, the peak of the chemical abundance distribution is at [Fe/H] ≈ -0.8. The metal-poor stars with [Fe/H] < -1 have halo kinematics, while the more metal-rich stars with [Fe/H] > -1 have typical bulge (or thick disk ?) kinematics. Their halo model indicates that only a small fraction of the Baade's window giants belong to the metal-poor halo, supporting the view that the bulge is *not* just the inner part of the halo.

For the future, it would be very interesting to know more about the kinematics of the intermediate abundance 47 Tuc-like population that pervades the outer bulge and the thick disk out to galactocentric distances R of at least 12 kpc. Not much is known about the kinematics of this population in the inner few kpc of the Galaxy.

5. Stellar Proper Motions in the Bulge

Proper motions are now becoming available for stars in the bulge. This is an important advance for understanding the dynamics of the bulge region, because proper motions and radial velocities give direct information about the rotation and kinematic isotropy of the bulge (eg Rich 1990). Proper motion data presented at this meeting (Minniti, Terndrup *et al*) indicate that the bulge is kinematically roughly isotropic in Baade's window and in a field at R = 1.6 kpc, with a velocity dispersion of about 110 km s^{-1}. There is a hint of tangential anisotropy for the more metal rich stars with [Fe/H] > 0.3. The stellar bulge as defined by the K giants is clearly rotating.

We look forward to more proper motion data for bulge stars, and to some absolute proper motions in the future.

6. The Abundance Gradient and Abundance Distribution

The observed abundance distribution for the inner bulge extends over the range $-1 < [Fe/H] < +1$, and is similar to that for the closed box model. Tyson reported on the radial abundance distribution along the minor axis of the bulge. The mean abundance appears to be roughly constant out to about 1.2 kpc from the center (near the edge of the COBE bulge) and then drops abruptly. This is an important observation, and we look forward to better statistics which will soon be available. The origin of the high mean abundance within the COBE bulge is not yet clear. Is it the product of early dissipational collapse and chemical evolution, or does it result from bar-driven starbursts in the inner bulge (see §9) ? The element ratios observed in the K giants of the bulge indicate moderate enhancement of the α-elements and enhancement of [Eu/Fe], suggesting a significant contribution from SN II to the chemical evolution.

Balcells found evidence for color gradients in the bulges of some external galaxies, particularly in the more luminous systems.

7. Structure and Content of other Bulges

Bulges appear to be dynamically close to isotropic oblate rotators, although the kinematics and light distributions show that some are clearly triaxial. Some bulges are boxshaped, like the bulge of our Galaxy; the incidence of boxiness in bulges is about 30 percent. The origin of this boxiness (vertical heating of the disk, oblique accretion, dissipative collapse ?) is not yet fully understood.

The high V/σ values and relatively low velocity dispersions of some apparent bulges, particularly in the later-type spirals, indicate that they are likely to be features in the disk (Kormendy). This suggests that secular evolution has taken place in these disks, possibly through bar formation.

Bulges and intermediate luminosity ellipticals show similar global properties, such as the color-magnitude and metallicity-luminosity relations (Bertola).

8. The Hot Stellar Component in the Bulge of M31

Studies of the hot stellar component in the bulge of M31 and in the ellipticals M32 and NGC 1399 (Ferguson) indicate that the incidence of classic post asymptotic giant branch stars falls as the abundance [Fe/H] increases (as predicted by Greggio and Renzini, 1990). This suggests that the incidence of planetary nebulae may be biased away from higher [Fe/H] values.

9. Bar Formation and Destruction, and the Bulge

Bar formation and destruction may be very important for the formation of bulges in disk galaxies, as discussed at this meeting by Hasan, Norman, Pfenniger and Sellwood. The sequence of events may proceed in this way:

1. Vertical resonances associated with bar formation pump disk stars into a box-shaped bar/bulge (here bar/bulge is just used to mean a barlike or triaxial bulge).
2. A bar is easily destroyed by a small central mass that is only a few percent of the total bar mass. This central mass affects the orbital structure of the bar, and transforms the bar into a roughly axisymmetric bulge-like system.
3. A bar in a disk galaxy drives a gas inflow which leads to a rapid aggregation of mass at the center of the bar (eg Wada's talk at this meeting). In this sense the bar provides the source of its own destruction. Central starbursts are associated with this gas flow, and these star-bursts may contribute significantly to the chemical enrichment of the inner bar/bulge.
4. This cycle of events may happen more than once: infall of cold gas into the inner regions of the disk may allow a bar to form again.

In this picture, normal bulges form from disk matter through the dynamical effects associated with bar formation and destruction. The accretion of a large (~ 10 percent) satellite can also lead to the formation of a bulge from disk matter. This may be appropriate to the formation of the larger bulges like that of the Sombrero galaxy NGC 4594.

If this picture of bulge formation through bar formation is correct, then we need to understand (as for any bulge formation picture) why so many late type disk galaxies (Sc and Sd) show no evidence for a bulge. Is it possible that these late type systems are stabilized against bar formation by their dark matter ? This seems unlikely, because late type barred galaxies are common enough. Or is the vertical pumping by the bar in these very flat systems less efficient over the lifetime of the bar ?

10. Some questions

10.1 THE AGE OF THE BULGE

To understand the sequence of events that led to the formation of the bulge, we need to know the relative ages of the metal-poor halo, the galactic bulge and the old disk in the inner Galaxy. It is important to have a definitive non-kinematical measurement of the age of the bulge. In the inner Galaxy, stellar kinematics may discriminate between populations older or younger than a few Gyr, but are unlikely to be reliable age indicators for older populations. Some age estimators that could be useful for the bulge include:

- Main sequence turnoff colors in Baade's window (Baum, King).

- The magnitude difference between the giant branch clump and the main sequence turnoff.
- Properties of the HB and RR Lyrae stars (eg Lee 1992).
- Limits on turnoff masses estimated from Preston's bulge Algol stars.
- Strömgren photometry of the evolved F/G star population in the bulge.

10.2 DISK-BULGE COEXISTENCE

Is there an old disk coexistent with the bulge, as in some ellipticals ? Or is there a Kormendy (1977) hole in the inner disk ? This question is relevant to the idea of bulge formation *via* bars. How could we tell ? For external galaxies, we would need detailed modelling to estimate the expected kinematical properties of stars along lines of sight passing through the inner disk and bulge. Then infrared photometric and spectroscopic observations of the inner regions of some edge-on bulges, may help to answer this question. For the inner regions of our Galaxy, studies of OH/IR sources are important for this problem (see §3). More proper motion work in low-latitude galactic windows would also be useful.

10.3 BAR/BULGES

We need to know more about the observational structure, kinematics and metallicity distribution of other small bar/bulges like that of NGC 4565 in order to interpret the observations of the galactic bulge. Realistic dynamical models of rotating bars would be very helpful for interpreting the observed structure and kinematics of small bar/bulges.

10.4 DYNAMICAL COMPARISON OF OUR BULGE WITH OTHERS

In other bulges, the kinematics are measured from integrated light (ie K giants) and planetary nebulae (for a few nearby systems like NGC 3115 and the Sombrero). It would be useful to exploit these techniques for the bulge of our Galaxy, in order to facilitate direct comparison of our bulge with others. Integrated light observations of the galactic bulge are straightforward in regions away from high interstellar absorption (eg Freeman *et al* 1988) but have not been used much so far. More extensive surveys for planetary nebulae in the galactic bulge, for detailed kinematical studies, would be easy and useful.

11. Conclusion

Bulges are interesting because they contain an important part of the history of galaxies like the Milky Way, and we need to know how the bulges fit in to the overall picture of galactic formation and evolution. Bulges may be the seeds for galaxy formation (at least for those galaxies that have bulges), or they may form later through dynamical effects (bar formation, accretion) acting on the disk. This makes the age determination of the galactic bulge particularly interesting. In the future, if we want to understand the events leading to the formation of bulges, then studies of galaxies at high redshift will surely be very important.

References

Freeman, K., de Vaucouleurs, G., de Vaucouleurs, A., Wainscoat, R. 1988. ApJ, 325, 563.
Greggio, L. & Renzini, A. 1990. ApJ, 364, 35.
Hunter, C. 1992. Presentation at Heidelberg Workshop: *Internal Dynamics of Ellipticals and Bulges.*
Kent, S. 1992. ApJ, 387, 181.
Kormendy, J. 1977. ApJ, 217, 406.
Lee, Y-W. 1992. Presentation at 11th Santa Cruz Workshop: *The Globular Cluster - Galaxy Connection.*
Rich, R.M. 1990. ApJ, 362, 604.
Rowley, G. 1988. ApJ, 331, 124.
Wyse, R. & Gilmore, G. 1988. AJ, 95, 1404.

DISCUSSION

Sellwood: Several different groups arguing on several different grounds, have all come to the conclusion that our galaxy is barred. What is reassuring about this is that they all put the angle of the bar in the same quadrant, although there is disagreement about the exact angle.

King: Are you bothered by the fact that the bar does not seem to show its signature in the stellar kinematics?

Freeman: Yes I am, but I'm still confused about what we are really looking, with the highly evolved objects.

Rich: I remain worried about the fact that we see these correlations between abundance and kinematics, and it seems hard to get them with the bar thickening mechanisms. Also, the correlations exist through the solar region of metallicity and above. So we are talking about the majority of stars in the Bulge, not just separating out halo and extremely metal rich.

Balcells: A basic test of the bar model for peanut shaped bulges, I think, is quite simple. If we place them on a V/σ v's flattening diagram, the behavior of oblate spheroids and bars should be quite different.

Michael FEAST