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THE GALACTIC BULGE

B. Barbuy

Universidade de São Paulo, IAG, Brazil

RESUMEN

Se describen y analizan los datos del Bulge y de cúmulos globulares teniendo en cuenta las teorías actuales acerca de la formación del Bulge

ABSTRACT

Data for Bulge field and globular clusters are described and discussed in the light of current theories of bulge formation.

Key Words: **GALACTIC BULGE — GLOBULAR CLUSTERS — STELLAR POPULATIONS**

1. INTRODUCTION

Two competing scenarios of bulge formation are a) the classical one, with a monolithic collapse in free-fall time, in which case the bulge forms first in about 10^8 years; b) the secular evolution of a bar, with transfer of disk gas and stars to the Galaxy center (Raha et al. 1991; Friedli & Benz 1995; Norman et al 1996). Gadotti & dos Anjos (2001) found that 25% of bulges of Sb and Sc galaxies present flat colour gradients, probably due to the action of a bar. It seems that bulges can be divided in two types: Sa, Sb galaxies have massive (and old) bulges, where Sc types have young bulges, sometimes even absent. Our Galaxy is an Sbc type (in fact SAB(rs)bc). According to Binney et al. (1997) the Galactic bulge is elongated and has axis ratios 1:0.6:0.4, with a semi-major axis of $\sim$ 2 kpc, and an elliptical disk of 2.5 kpc $\times$ 3.5 kpc surrounds the bulge.

2. THE GALACTIC BULGE

Whitford & Rich (1983) revealed that the bulge is metal-rich and that the integrated spectrum of Baade's Window (b=-4°) resembles spectra of bulges of other spirals and E/S0 galaxies. Ortolani et al. (1995) revealed that the globular clusters NGC 6528 and NGC 6553 are templates of the bulge stellar population, and that they are have ages nearly coeval with the halo. On the other hand, young massive stars are observed near the Galactic center: Frogel et al. (1999) found that they decline in density beyond 1°, whereas Ramirez et al. (2000) analysed 110 M giants and concluded that they are a mixture of young massive giants and older Asymptotic Giant Branch stars (AGBs).

3. BULGE GLOBULAR CLUSTERS

The bulge globular clusters form a flattened system extending to 4.5 kpc from the Sun. They are important probes as tracers of the structure of the bulge (e.g. Barbuy et al. 1998), their age and chemical properties are indicators of the process of Galaxy formation (Ortolani et al. 1995), and their spectra are templates for the study of composite stellar populations in ellipticals and bulges of early spirals (e.g. Bica 1988).

It is important to point out that new bulge globular clusters were reported recently in the literature: Hurt et al. (2000) discovered two new globulars 2MASS-GC01 (l=10.47°, b=0.10°), 2MASS-GC02 (l=9.78°, b=0.62°), whereas Ortolani et al. (2000) revealed that ESO 280-SC06, previously classified as an open cluster is in fact a globular cluster. These 3 clusters, together with the compilation of globular clusters by Harris (1996, as updated in http://physun.physics.mcmaster.ca/Globular.html), make that there are 150 known globular clusters in the Galaxy. Note in addition that Dutra & Bica (2000) used 2MASS to propose a list of candidates towards the Galactic center.

There are 74 globular clusters projected within 20°×20° of the Galactic center, among which 60 have galactocentric distances $R_{GC} < 4$ kpc. In Barbuy et al. (1999) it was shown that most of the inner clusters have red Horizontal Branches (HB), whereas the number of blue HBs increases towards larger distances of the Galactic center. Most of the inner clusters are metal-rich, but a number of them are metal-poor, such as: Terzan 4, Terzan 9, NGC 6139 and NGC 6453 of [Fe/H] $\approx$ -2.0, and HP 1, NGC 6522, NGC 6558, NGC 6256, NGC 6717 of intermediate metallicities -1.5 < [Fe/H] < -1.0. These clusters could be the oldest objects of the Galaxy, if they were formed first as proposed by van den Bergh (1993). Therefore it would be important to determine their ages.

The metallicity of the 60 inner clusters, based on the updated list of Harris (1996), is shown in Fig. 1. Two metallicity peaks are seen, at [Fe/H] $\approx$ -1.5 and -0.5 (similarly to the majority of extragalactic globular cluster systems - see IAU Symp. 207 by Grebel et al. 2001). The most inner clusters within 5° of the Galactic center, shown in Fig. 2, have metallicities more around [Fe/H] $\approx$ -0.5 (Barbuy et al. 1998; Ortolani et al. 1999), with a distribution similar to that of field stars as given in McWilliam & Rich (1994).

3.1. *Is there a connection between bulge and thick disk or bar?*

Minniti (1995) has shown that the spatial distribution of the inner metal-rich clusters is more consistent with a bulge population than with a thick disk structure. He also showed that the bulge clusters have a rotation of a solid body. Côté (1999) found essentially the same as Minniti (1995) regarding the solid body rotation of the inner metal-rich clusters, and noted that the most inner metal-poor clusters also follow such rotation pattern. Côté showed as well a correlation between the location of metal-rich clusters and HI gas in the central parts of the Galaxy, which would be a hint on a bar-bulge scenario.

The relative proper motion of NGC 6553 resulted in velocities (Π, Θ, W) = (-3.5, 230, -3) km s^{-1} (Zoccali et al. 2001). This rotational velocity is consistent both with the mean rotation of the bulge at 2.7 kpc (location of NGC 6553) cf. Minniti (1995), and the disk rotation at the same distance (Amaral et al. 1996). Therefore NGC 6553 could belong to the disk from this point of view. On the other hand, it is old, and very similar to NGC 6528, located in Baade's Window, with a radial velocity of $v_r \approx 215$ km s^{-1}. The old age of NGC 6528 and NGC 6553 was demonstrated based on optical V and I CMDs (Ortolani et al. 1995; Zoccali et al. 2001), and also based on J and H CMDs obtained using NICMOS on board the Hubble Space Telescope, as shown in Ortolani et al. (2001).

4. ABUNDANCES IN THE GALACTIC BULGE

As concerns abundances in the Galactic bulge, the question is if (i) the bulge is very old, as predicted in models of inside-out galaxy formation (Larson 1990), one expects the abundances in the bulge to be dominated by supernovae type II, which leave their signature of enhancements of α-element abundances with respect to iron ([α-element/Fe] > 0).

(ii) if the bulge is the result of a dynamical evolution of a bar, and consequently the gas and stars in the bulge are disk-like, one expects solar α-element to iron ratios ([α-element/Fe] $\approx$ 0).

Other formation scenarios for the bulge are:

(iii) a third possibility suggested in the literature is the capture of dwarf galaxies, which seems however ruled out since there is no anti-rotation in the bulge, such as found in the halo, and also due to the fact that dwarf galaxies are metal-poor, and the bulge is metal-rich.

(iv) Finally, merging of disks are suggested as the mechanism to form bulges, however detailed calculations are not available so far.

Matteucci & Brocato (1990) and Matteucci et al. (1999) have computed the build up of chemical elements for a bulge model with enhanced star formation rate and timescale for collapse of the bulge of $\sim 10^7$ yr. Mollà et al. (2000) also presented chemical evolution models for the bulge. The predictions by Matteucci et al. give enhancements of α-elements, for example for oxygen, up to [Fe/H] $\sim$ 0, whereas Mollà et al. find that at [Fe/H $\sim$ -0.5 oxygen to iron reaches [O/Fe] $\sim$ 0.

Very few high resolution abundance determinations are available for bulge stars. The now classical work by McWilliam & Rich (1994) contained the high resolution abundance analysis of 11 Baade's Window field giants. They obtained: $[Mg/Fe] \approx [Ti/Fe] \approx 0.3$, whereas $[Ca/Fe] \approx [Si/Fe] \approx 0$.

As concerns bulge clusters two Red Giant Branch (RGB) stars by Barbuy et al. (1999) and 5 HB stars by Cohen et al. (1999) of NGC 6553 were analysed. The results are conflicting: Barbuy et al. find [Fe/H] = -0.55, together with excesses of α-elements, whereas Cohen et al. find [Fe/H] = -0.16 with small excesses of α-elements. It is important to note that the two sets of results are not in significant conflict as regards the overall metallicity $[Z/Z_{\odot}]$ = -0.27 for Barbuy et al. and +0.16 (or -0.12 considering that their oxygen abundances based on the triplet infrared lines are overestimated) for Cohen et al. The mean for Baade's Window stars by McWilliam & Rich gives $[Z/Z_{\odot}]$ = -0.12. More recently Carretta et al. (2001) analysed 4 HB stars in NGC 6528, having found [Fe/H] = +0.07.

The conflict of results between Barbuy et al. (1999) for giants and Cohen et al. (1999) for HB stars can be due to different problems in the anal-

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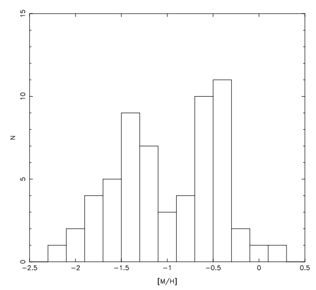

Fig. 1. Metallicity distribution of the 60 inner clusters, located within $20° \times 20°$ and $R_{GC} < 4$ kpc of the Galactic center. Metallicity values are from Harris (1996).

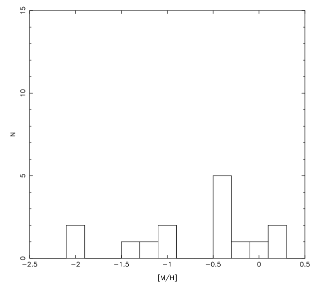

Fig. 2. Metallicity distribution of the 17 inner clusters, located within $5° \times 5°$, using metallicity values from Barbuy et al. (1998) and Ortolani et al. (1999).

ysis of both samples. The ATLAS and NMARCS model atmospheres for HB stars show differences in their temperature structure, as was discussed for the case of the metal-poor globular cluster NGC 6397 by Castilho et al. (2000); on the other hand in the cool RGB stars TiO bands make a continuum problem, as can be seen in Fig. 5 of Coelho et al. (2001). These latter authors have obtained metallicities of a sample of RGB to HB stars in NGC 6528 and NGC 6553, by comparing synthetic spectra computed with ATLAS models to the observations: higher metallicities are found for the HB stars relative to the RGB stars, which indicates that a problem with the structure of model atmosphere does play a rôle in this question.

Finally, abundances of planetary nebulae in the Galactic bulge are discussed by Maciel (1999) and Escudero & Costa (2001).

5. CONCLUSIONS

The Galactic bulge seems to consist of two subsystems together:

a) A dominant metal-rich old bulge, of [Fe/H] > -1.0, which extends to 5° of the Galactic center

b) A young central disk population, confirmed by the central cluster with diameter of 0.7 arcmin, and the young open clusters Arches and Quintuplet, projected 50 pc from the nucleus; these are very central and with very low height scale z. Besides, there are Miras and intermediate age Planetary Nebulae. This young and intermediate age component is probably the result of the action of the bar, which would provide gas in the center.

The formation of the bulge can be tested by abundance ratios of older stars, to probe the possibility of an intense and fast star formation at early times. Further high resolution abundance analyses of bulge stars are urgently needed.

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