Mem. S.A.It. Vol. 86, 182

Memorie della

The Galactic bulge

B. Barbuy[1], S. Ortolani[2], and E. Bica[3]

[1] Universidade de São Paulo, IAG, Rua do Matão 1226, Cidade Universitária, São Paulo 05508-900, Brazil, e-mail: barbuy@astro.iag.usp.br
[2] Università di Padova, Dipartimento di Fisica e Astronomia Galileo Galilei, Vicolo dell'Osservatorio 2, I-35122 Padova, Italy, e-mail: sergio.ortolani@unipd.it
[3] Universidade Federal do Rio Grande do Sul, Departamento de Astronomia, CP 15051, Porto Alegre 91501-970, Brazil, e-mail: bica@if.ufrgs.br

Abstract. We describe currently discussed models for bulge formation. Data available on age and metallicity for field and globular cluster bulge stellar populations are presented, including most recent evidence on X-shape bulge and He-enrichment. We also report on recent evidence for early chemical enrichment by massive spinstars.

Key words. Galaxy: bulge – Galaxy: abundances

1. Introduction

Scenarios of bulge formation imply in different kinematical and chemical abundance characteristics. In this paper we describe models of bulge formation, and try to interpret the available data in terms of best model.

The classical scenario for bulge formation consists of a monolithic collapse, in a free-fall time $t_{ff} \sim (G\rho)^{-1/2}$. In this case the bulge forms first in the Galaxy, in a timescale of $\sim 10^8$ years, as described 50 years ago by Eggen, Lynden-Bell & Sandage (1962). An opposite scenario is the secular evolution, where a bar forms and the bulge is formed later from gas and stars transferred from the bar to the Galactic center (Raha et al. (1991), Friedli & Benz (1996), Combes (2007), Athanassoula (2008), Binney (2008). If stars are transferred from the bar to the bulge, then the chemical composition of bulge stars should be similar to inner disk stars, whereas if gas is transferred, and then the bulge forms stars, this would be equivalent to bulge forming stars first; in the latter case we would have no way to distinguish between the classical and secular evolution scenarios.

Bournaud et al. (2009) computed the formation of bulge and thick disk of Milky Way-analog galaxies, in particular NGC 891. Disk galaxies accrete most of their mass smoothly, and acquire their structure by stellar processes (scattering) through turbulent and clumpy phases at high redshift. The formation of bulge and thick disk occurs early in their formation, and no bars are included in these simulations.

Finally, in ΛCDM simulations, gas falls in filaments in dark matter halos at redshifts z$\sim$5, then gas cools and condenses. Star clumps merge together, and matter drains down to filamentary structure into the most massive progenitor (Abadi et al. 2003). In summary, small disks form first, then the merge together: bulges form first in galaxies.

According to Kormendy & Kennicutt (2004), secular evolution is dominant in Sc galaxies where pseudobulges form. In Sa and Sb galaxies, the more massive and old true bulges should have formed first in the galaxy. In this context, the question is about our Galaxy, of type SAB(rs)bc: is its bulge a pseudo or a true bulge, or a mixture of the two processes.

2. Observational evidence

SED of the Galactic bulge, as compared with Ellipticals, Sa and Sc was presented by Zoccali et al. (2003), showing that our Galaxy cannot be identified to an Sc galaxy. The magnesium abundance index $Mg_2 = 0.23$, whereas in Ellipticals it is typically $Mg_2 = 0.32$.

Zoccali et al. (2003) and Clarkson et al. (2008) have shown that Colour-Magnitude Diagrams of the bulge indicate that field stellar populations are as old as halo clusters. The metal-rich globular clusters were shown to be coeval with the halo by Ortolani et al. (1995). The bulge metal-poor globular clusters should have formed earlier and be naturally older than metal-rich ones, as discussed in the next section.

The field bulge stellar population was investigated by Zoccali et al. (2008) with the observation of 800 stars in 4 locations, with galactic coordinates l, b at Baade's Window (1.14°, -4.2°), -6° (0.2°, -6°), -12° (0°, -12°), and near NGC 6553 (5.2°, -3°). This study has shown that there is a metal-rich population at [Fe/H]$\sim$+0.3 that only appears in the inner parts, and disappears in higher latitude regions. This was recently confirmed by Bensby et al. (2011). More importantly, a kinematical study of these populations by Babusiaux et al. (2010) demonstrated that the metal-rich population can be assigned to a bar population, whereas the solar-like metallicity and metal-poor populations have kinematics characteristic of classical bulges, i.e. spheroids or thick disks.

2.1. Chemical abundances

Chemical evolution models by Cescutti & Matteucci (2011) assume an intensified star formation rate by a factor 10, resulting in a bulge enrichment on a timescale of 10^7 years.

Enhanced O, Mg are confirmed by Zoccali et al. (2006), Fulbright et al. (2006), Lecureur et al. (2007), Gonzalez et al. (2011) and Si, S enhancements are confirmed by Alves-brito et al. (2010), Ryde et al. (2009), Bensby et al. (2010).

3. Metal-poor bulge globular clusters

A first generation of massive stars could have formed as early as redshifts z$\sim$35 according to Gao et al. (2010). A second generation of long-lived low-mass stars would then form in the inner parts of galaxies.

Barbuy et al. (2009) identified a sample of moderately metal-poor globular clusters with [Fe/H]$\sim$-1.0, and blue horizontal branches. This combination of characteristics should indicate that they are very old, probably the oldest objects in the Galaxy. An estimation of the age of NGC 6522 indicates that it should be at least 2 Gyr older than the mean of globulars reported in Marin-Franch et al. (2009) - see Fig. 10 by Barbuy et al. (2009).

The abundance pattern of these clusters was investigated so far for HP 1, NGC 6522 and NGC 6558, and they agree with each other. One exception is the s-element enrichment in stars of NGC 6522. An interesting interpretation of high Ba, Y, Sr, La in stars of NGC 6522, is the possibility of an early enrichment by massive spinstars, as discussed in Chiappini et al. (2011). A rotational mixing transports ^{12}C from He-burning core into H-rich layers where it is transformed to ^{14}N and ^{13}C. This primary ^{14}N is transported back to He core and converted to ^{22}Ne, that is the main neutron source. s-process then occurs in hydrostatic He-core burning and a primary s-process Ba is produced. Europium and some Ba is also produced through the r-process in the Supernova explosion.

A further aspect of these clusters that need deeper investigation is their helium content. As discussed in the next Section, there is some evidence for high helium abundance in the bulge. If these metal-poor clusters are helium-rich, they would be younger.

4. New evidence on the bulge: X-shape

Saito et al. (2012), McWilliam & Zoccali (2010) have made evident that there are two red clumps in the bulge, at different distances corresponding to 6.5 kpc and 8.0 kpc, at all galactic coordinates l, b covered by the VVV survey (Saito et al. 2012). This revelation was predicted earlier by Athanassoula (2005), and is denominated as an X-shape.

5. New evidence on the bulge: helium enrichment?

A high helium abundance is predicted in two scenarios: Ejecta from Asymptotic Giant Branch (AGB) stars of high mass (3 - 10 $M_\odot$) should yield a helium abundance of Y=0.33 (Renzini 2008); in models of early enrichment by fast rotating massive stars, a helium abundance as high as Y=0.50 is expected (Decressin et al. 2007).

Nataf et al. (2011) have adopted a ratio of number of Red Giant Bump (RGB) stars to Red Clump (RC) stars as indicators of helium abundance. From OGLE-III Detection of the anomalous Galactic bulge RGB Bump, they found evidence of enhanced helium enrichment. Turn-off location of microlensed dwarfs also seem to indicate a high He. Values of RGBbump/RC~0.1 indicate a high He.

We have measured RGBBump/R~0.3 in NGC 6553, and RGBBump/RC~0.9 in HP 1, in both cases indicating a normal He abundance. Therefore from a metal-rich and a metal-poor globular cluster such evidence is not confirmed.

6. Conclusions

If X-shape is an indication of a pseudobulge, there remains to explain the kinematic difference between metal-poor and metal-rich stars as revealed by Babusiaux et al. (2010). On the other hand, metal-poor stars are a tiny fraction of the bulge population, that could be very old and formed in an early bulge collapse.

There remains to explain the alpha-element enhancement also in the metal-rich population. It could be however that all the structure could be very old, with thick disk and bulge forming early from secular bar evolution. The X-shape could have formed in the first 1 Gyr.

Metal-poor globular clusters could be the oldest objects in the Galaxy. The estimation of their age would give younger ages if He is enhanced. For this, further counts on blue extended Horizontal Branch globular clusters are needed. Our counts on the metal-poor globular HP 1 and in the metal-rich inner bulge globular NGC 6553 indicate no He enhancement.

Finally, bulge field and globular clusters should be further investigated for their heavy-element abundances, in order to check on further evidence on enrichment by fast rotating massive stars.

Acknowledgements. BB and EB acknowledge grants from brazilian agencies FAPESP, CNPq and CAPES. SO acknowledges grants from Ministero della Ricerca.

References

Abadi, M. G., et al. 2003, ApJ, 591, 499
Alves-Brito, A. et al. 2010, A&A, 513, 35
Athanassoula, E. 2005, MNRAS, 358, 1477
Athanassoula, E. 2008, M. Bureau, E. Athanassoula, B. Barbuy eds. (Cambridge Univ. Press, Cambridge), IAU Symp. 245, 93
Babusiaux, C. et al. 2010, A&A, 519, 77
Barbuy, B. et al. 2009, A&A, 507, 405
Bensby, T. et al. 2010, A&A, 512, 41
Bensby, T. et al. 2011, A&A, 533, 134
Binney, J. 2008, M. Bureau, E. Athanassoula, B. Barbuy eds. (Cambridge Univ. Press, Cambridge), IAU Symp. 245, 455
Bournaud, F., Elmegreen, B. & Martig, M. 2009, ApJ, 707, L1
Cescutti, G., & Matteucci, F. 2011, A&A, 525, 126
Chiappini, C., Frischknet, U., Meynet, G. 2011, Nature, 472, 454
Combes, F. 2007, F. Combes, J. Palous eds. (Cambridge Univ. Press, Cambridge), IAU Symp. 235, 19
Decressin, T., Charbonnel, C. & Meynet, G. 2007, A&A, 475, 859

Eggen, O. J., Lynden-Bell, D., Sandage, A. R. 1962, ApJ, 136, 748
Friedli, D., Benz, W. 1995, A&A, 301, 649
Fulbright, J. A., McWilliam, A. & Rich, R.M. 2007, ApJ, 661, 1152
Gao, L., Theuns, T., Frenk, C. S. 2010, MNRAS, 403, 1283
Gonzalez, O. A. et al. 2011, A&A, 503, 54
Lecureur, A. et al. 2007, A&A, 465, 799
Kormendy, J., Kennicutt, R. C. Jr. 2004, ARA&A, 42, 603
Marin-Franch, A., Aparicio, A., Piotto, G. 2009, ApJ, 694, 1498
Nataf, D.M.,et al. 2011, ApJ, 730, 118
McWilliam, A., Zoccali, M. 2010, ApJ, 724, 1491
Ortolani, S., Renzini, A., Gilmozzi, R. 1995, Nature, 377, 701
Raha, N., et al. 1991, Nature, 352, 411
Renzini, A. 2008, MNRAS, 391, 354
Ryde, N. et al. 2010, A&A, 509, 20
Saito, R. et al. 2012, A&A, 544, 147
Zoccali, M. et al. 2006, A&A, 457, L1
Zoccali, M., Renzini, A., Ortolani, S. 2003, A&A, 399, 931
Zoccali, M., Lecureur, A., Hill, V. 2008, A&A, 486, 177