The Galaxy Disk in Cosmological Context
Proceedings IAU Symposium No. 254, 2008
J. Andersen, J. Bland-Hawthorn & B. Nordström, eds.

doi:10.1017/S1743921308027543

Unveiling the Secrets of the Galactic bulge through stellar abundances in the near-IR: a VLT/Crires project

Nils Ryde[1]

[1]Lund Observatory, Box 43, SE-221 00 Lund, Sweden
email: ryde@astro.lu.se

Abstract. The formation and evolution of the Milky Way bulge can be constrained by studying elemental abundances of bulge stars. Due to the large and variable visual extinction in the line-of-sight towards the bulge, an analysis in the near-IR is preferred. Here, I will present some preliminary results of an on-going project in which elemental abundances, especially those of the C, N, and O elements, of bulge stars are investigated by analysing CRIRES spectra observed with the VLT.

Keywords. stars: abundances, Galaxy: bulge, infrared: stars

---

1. What Type is the Milky Way bulge?

A bulge is clearly different from its surrounding components: For instance, there are in general, a distinct radial surface brightness peak, specific stellar populations, different kinematics, and less interstellar medium. Although bulges of galaxies form a heterogeneous class of objects, Kormendy & Kennicutt (2004) define two classes of bulges based on the way they are formed: First, the merger-built classical bulges and, second, the secularly evolved ones (pseudo-bulges). These are not clear-cut groups. Galaxies continue to evolve after merger events and can thus exhibit both signatures of a classic bulge and a secularly evolved one. Bulges of the first class are formed through hierarchical clustering and merging events and are similar to elliptical galaxies (bulges of early-type galaxies can therefore be seen as ellipticals in the center of disks). Further, these bulges have had star formation long ago and therefore contain mostly old stars. The second group, the pseudo-bulges, are evolved through slow secular evolution and are important in medium-to-late-type galaxies. Galaxies with pseudo-bulges can not have experienced a merging event for a long time. They are further made slowly out of disk gas and retain a memory of their disk origin, can have ongoing star formation, and exhibit young stars. These two types of bulges give different dynamical and chemical signatures.

The Milky Way is a spiral galaxy, with a pronounced bulge and a small bar, dynamic and transient in nature. The Bulge has a peanut-form profile and its structure and shape have signatures of the secularly evolved pseudo-bulges, but the age of the stellar population(s) and α-element enhancement (O, Mg, Si, Ca, Ti) are signatures of classical bulges. In spite of the fact that the origin, age, and chemical properties of the Bulge remain poorly understood, there is a consensus that there exists a dominant, old, metal-rich population in the Bulge. The bulk of the Bulge's stellar population is thought not to have formed by slow secular evolution. E.g. Zoccali *et al.* (2003) find no trace of a younger population in the Bulge. However, in the Galactic center, within of the order of 100 pc of the geometrical center, there is some evidence of ongoing star formation and a younger population (see e.g. Figer *et al.* (2004) and Barbuy (2002)).

Thus, the formation of the Milky Way bulge is clearly not well understood and its classification is inconclusive. However, the different formation scenarios can be constrained by abundance surveys. From stellar populations and abundance analyses it can be investigated which process dominated the star formation: whether stars formed rapidly a long time ago during hierarchical clustering of galaxies (as a classical bulge), or through secular evolution (such as defines a pseudo-bulge). The α-element composition (e.g. O, Mg, Ca, etc.) relative to iron as a function of the metallicity, [Fe/H], can infer star-formation rates (SFR) and initial-mass functions (IMF) from stellar compositions. A shallower IMF will increase the number α-element producing stars thus leading to higher $[\alpha/\mathrm{Fe}]$ values. A faster enrichment due to a high star-formation rate will keep the over-abundance of the α elements at a high value also at higher metallicity. Different populations may show different behaviours.

2. Advantages of a Spectral Analysis in the Near-IR

The Bulge has remained fairly unexplored, mainly because of the large optical obscuration due to dust in the line-of-sight toward the Galactic center. A spectroscopic investigation of elemental abundances based on near-IR spectra alleviates this problem. The Bulge is more accessible in the IR than in the optical for multiple reasons (Ryde *et al.* 2005). The most important is of course the smaller interstellar extinction in the IR ($\mathrm{A_K} \sim 0.1 \times \mathrm{A_V}$; Cardelli *et al.* 1989). Furthermore, red stars stand out the most in the near-IR not only because they are brightest there. Admittedly, the dust extinction decreases monotonically with wavelength, which favors longer wavelengths, but interstellar dust radiates strongly in the mid- and far-IR, thus favoring the near-IR. Furthermore, in the thermal infrared (i.e. beyond approximately 2.3 μm) the telluric sky starts to shine due to its intrinsic temperature, making observations increasingly more difficult. Thus, this leaves us with the J, H, and K bands for an optimal spectroscopic study. The near-IR is also preferred for analysis of abundances, due to the fact that the absorption spectra are less crowded with lines, that fewer lines are blended, and that it is easier to find portions of the spectrum which can be used to define a continuum compared to wavelength regions in the optical spectral window. Since the transitions occur within the electronic ground-state, the assumption of *Local Thermodynamic Equilibrium (LTE)* in the analysis of the molecules is probably valid (Hinkle & Lambert 1975), which simplifies the analysis dramatically. Moreover, in the Rayleigh-Jeans regime, the intensity is less sensitive to temperature variations. This means that the effects of, for example, effective-temperature uncertainties or surface inhomogeneities on line strengths should be smaller in the IR. Clearly, the near-IR is the optimal spectroscopic region to work in, in order to get a handle on the Milky Way bulge through an abundance analysis.

Recently, a few studies of elemental abundances of bulge stars using near-IR spectra at high resolution have been done, see for instance Meléndez *et al.* (2008), Cunha *et al.* (2007), Cunha & Smith (2006), and Meléndez *et al.* (2003).

3. Drawbacks of a Spectral Analysis in the Near-IR

A general drawback of a spectral analysis in the near-IR is that there are much fewer atomic and ionic lines. The ones that exist often originate from highly excited levels in metals, which also complicates an interpretation. Furthermore, many lines are not properly identified and/or lack known atomic line-strengths, which are needed in an abundance analysis. There are, however, many molecular lines in this region which can be used. Note, though, the lack of signatures from several molecules such as TiO and ZrO

https://doi.org/10.1017/S1743921308027543 Published online by Cambridge University Press

in the near-IR. Furthermore, even though large advances have been made when it comes to the technology for recording near-infrared light, existing spectrometers are still much less effective than optical ones, one of the main reasons being the lack of cross-dispersion. Finally, determining the stellar parameters based only on near-IR spectra is difficult.

4. Unveiling the secrets of the Galactic bulge: an infrared spectroscopic study of Bulge giants

We† are engaged in an on-going VLT project (080.D-0675), in which we are analysing near-IR spectra recorded at a spectral resolution of $R = 60,000$ with the CRIRES spectrometer (Moorwood 2005; Käufl *et al.* 2006) on the *Very Large Telescope, VLT*, see also Ryde *et al.* (2007). The aim of the project is to draw firm conclusions on the formation history of the Galactic bulge by obtaining precise abundances of C, N, and O in addition to α elements (Mg, Si, S, Ca, and Ti), and a few other elements for a well-chosen sample of stars, sampling different stages of the chemical enrichment history and different parts of the Bulge. Here, we present the first three stars, chosen from Arp (1965), namely Arp 4329, Arp 4203, and Arp 1322 (see Table 1) in Baade's Window. The H-magnitudes of the stars range from $H = 9.2 - 11.1$ and the exposure times from $100 - 300$ s. The spectra will be shown and presented in more detail in Ryde *et al.* (2008, in prep.).

The CRIRES spectrometer records approximately a three times broader wavelength range compared to, for instance, the Phoenix spectrometer (Hinkle *et al.* 1998, 2003), which is an important advantage. Note, however, that the signal-to-noise over the CRIRES wavelength range may vary by a factor of two. In the range we have observed, we have identified many CO, CN, and OH lines, 10 Si, 5 Ti, 4 S, 5 Ni, one Cr, and many Fe lines. The modelling of the atmospheres, the determination of the line strengths, a discussion on the sensitivity of the molecular lines caused by *(i)* changes in the C, N, O abundances by 0.1 dex, and *(ii)* uncertainties in the stellar parameters, will be presented in Ryde *et al.* (2008, in prep.). The abundances of Mg, Si, Al. and Na are important for the calculation of the model atmosphere since these elements are important electron donors and thereby affect the electron pressure in the atmosphere. Also, the continuous opacity which directly affects line strengths, is due to H^- free-free, which depends on the electron pressure. In Figure 1, the relative importance of these different elements as electron donors are shown versus the Rosseland optical depth in the model atmosphere of the bulge star Arp 1322. Therefore, it is important to know these abundances, also when investigating other elements. For a further discussion, see Ryde *et al.* (2008 in prep.).

The resulting abundances are presented Table 2. A good agreement is found between our near-IR results and the abundances from Fulbright et al (2007), an analysis based on optical spectra. This is reassuring for future analysis of stars for which only near-IR spectra will exist. It should be noted that a general problem with determining elemental abundances for stars with only near-IR spectra is, however, the temperature sensitivity of the molecular lines and the difficulties in the determination of the stellar parameters.

5. Conclusions

Stellar surface abundances in Bulge stars, especially those of the C, N, and O elements, can be extensively studied in the near-IR, due to lower extinction. Here, we have shown

† B. Edvardsson, B. Gustafsson (PI), A. Alves Brito, M. Asplund, B. Barbuy, K. Eriksson, V. Hill, K.. Hinkle, S. Johansson, H.-U. Käufl, D. L. Lambert, A. Lecureur, J. Melendez, D. Minniti, S. Ortolani, F. Primas, A. Renzini, N. Ryde, V. V. Smith, and M. Zoccali

https://doi.org/10.1017/S1743921308027543 Published online by Cambridge University Press

Table 1. Stellar parameters for the three stars presented here. The parameters are taken from Fulbright *et al.* (2007).

Star	$T_{\rm eff}$ [K]	$\log g$ cgs	[Fe/H]	$\xi_{\rm micro}$ [km s^{-1}]
Arp1322	4106	0.89	−0.23	1.6
Arp4203	3902	0.51	−1.25	1.9
Arp4329	4197	1.29	−0.90	1.5

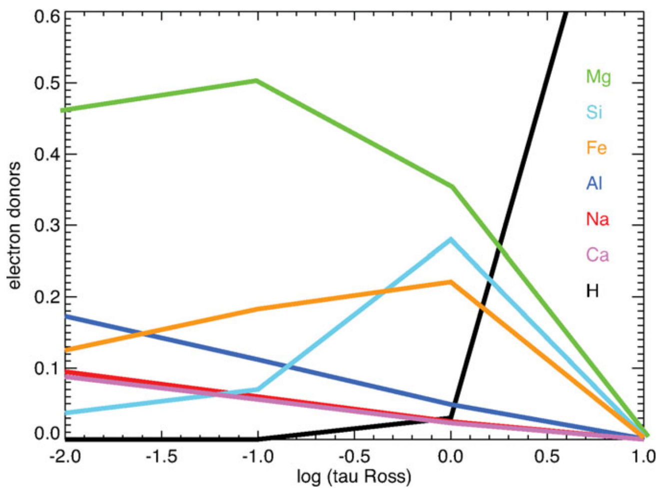

Figure 1. Elements contributing to the electron pressure in the model atmosphere of the Bulge star Arp 1322. The electron pressure affects the continuous opacitiy which directly affects the equivalent widths of spectral lines. At 1.5 μm the continuum is formed at $\log \tau_{\rm Ross} \sim 0.5$, and the lines of the molecules are formed further out, namely at $\log \tau_{\rm Ross}^{\rm CO} \sim 0.2$, $\log \tau_{\rm Ross}^{\rm CN} \sim 0.1$, and $\log \tau_{\rm Ross}^{\rm OH} \sim -2.4$.

a good agreement between near-IR and optically determined abundances in stars in Baade's window, stars which can be observed in both wavelength ranges. It will be very important to extend the analysis to other regions of the Galactic bulge, such as in the galactic plane, in order to get a proper handle on its formation and evolution. In these regions the optical extinction is large which only permits observations in the near-IR. Near-IR, high-spectral-resolution spectroscopy offers a promising methodology to study the whole Bulge to give clues to its formation and evolution.

References

Arp, H., 1965, ApJ 141, 43

Barbuy, B., 2002, in J. J. Claria, D. Garcia Lambas, & H. Levato (eds.), Revista Mexicana de Astronomia y Astrofisica Conference Series, Vol. 14 of Revista Mexicana de Astronomia y Astrofisica, vol. 27, p. 29

Cardelli, J. A., Clayton, G. C., & Mathis, J. S., 1989, ApJ 345, 245

Cunha, K., Sellgren, K., Smith, V. V., *et al.*, 2007, ApJ 669, 1011

Cunha, K. & Smith, V. V., 2006, ApJ 651, 491

Figer, D. F., Rich, R. M., Kim, S. S., Morris, M., & Serabyn, E., 2004, ApJ 601, 319

Fulbright, J. P., McWilliam, A., & Rich, R. M., 2006, ApJ 636, 821

Fulbright, J. P., McWilliam, A., & Rich, R. M., 2007, ApJ 661, 1152

Table 2. Abundances of C, N, O, Ti, Si, S, Cr, Ni, and Fe for Arcturus and three bulge giants as determined from our near-IR spectra observed with VLT/CRIRES. As a comparison the abundances for the same stars determined by Fulbright *et al.* (2006, 2007) are also provided.

Star	**Ref.**	$\log\varepsilon(\mathrm{C})^{a}$ [dex]	$\log\varepsilon(\mathrm{N})$ [dex]	$\log\varepsilon(\mathrm{O})$ [dex]	$\log\varepsilon(\mathrm{Ti})$ [dex]	$\log\varepsilon(\mathrm{Si})$ [dex]	$\log\varepsilon(\mathrm{S})$ [dex]	$\log\varepsilon(\mathrm{Cr})$ [dex]	$\log\varepsilon(\mathrm{Ni})$ [dex]	$\log\varepsilon(\mathrm{Fe})$ [dex]
Arcturus	this work	8.06	7.67	8.76	4.68	7.35	6.94	5.17	5.78	7.00
	Fulbright *et al.*	–	–	8.67	4.68	7.39	–	–	–	6.95
	difference	–	–	0.09	0.00	−0.04	–	–	–	0.05
Arp 4203	this work	6.62	7.70	7.71	3.98	6.75	6.26	4.28	5.12	6.25
	Fulbright *et al.*	–	–	7.55	4.03	6.82	–	–	–	6.20
	difference	–	–	0.16	−0.05	−0.07	–	–	–	0.05
Arp 4329	this work	7.42	7.23	8.25	4.33	7.15	6.81	4.77	5.41	6.60
	Fulbright *et al.*	–	–	8.16	4.30	7.14	–	–	–	6.55
	difference	–	–	0.09	0.02	0.01	–	–	–	0.05
Arp 1322	this work	7.93	8.10	8.61	4.87	7.52	7.35	5.62	6.02	7.33
	Fulbright *et al.*	–	–	8.80	4.84	7.43	–	–	–	7.22
	difference	–	–	−0.19	0.03	0.09	–	–	–	0.11

Notes:
[a] $\log\varepsilon(\mathrm{X}) = \log n_{\mathrm{X}}/n_{\mathrm{H}} + 12$, where $\log n_{\mathrm{X}}$ is the number density of element X.

Hinkle, K. H., Blum, R. D., Joyce, R. R., *et al.*, 2003, in P. Guhathakurta (ed.), Discoveries and Research Prospects from 6- to 10-Meter-Class Telescopes II. Edited by Guhathakurta, Puragra, Vol. 4834 of Proc. SPIE, p. 353

Hinkle, K. H., Cuberly, R. W., Gaughan, N. A., *et al.*, 1998, SPIE 3354, 810

Hinkle, K. H. & Lambert, D. L., 1975, MNRAS 170, 447

Käufl, H. U., Amico, P., Ballester, P., *et al.*, 2006, The Messenger 126, 32

Kormendy, J. & Kennicutt, Jr., R. C., 2004, ARA&A 42, 603

Meléndez, J., Asplund, M., Alves-Brito, A., Cunha, K., Barbuy, B., Bessell, M. S., Chiappini, C., Freeman, K. C., Ramírez, I., Smith, V. V., & Yong, D., 2008, A&A 484, L21

Meléndez, J., Barbuy, B., Bica, E., *et al.*, 2003, A&A 411, 417

Moorwood, A., 2005, in H. U. Käufl, R. Siebenmorgen, & A. F. M. Moorwood (eds.), High Resolution Infrared Spectroscopy in Astronomy, p. 15

Ryde, N., Edvardsson, B., Gustafsson, B., & Käufl, H.-U., 2007, in A. Vazdekis & R. F. Peletier (eds.), IAU Symposium, Vol. 241 of IAU Symposium, p. 260

Ryde, N., Gustafsson, B., Eriksson, K., & Wahlin, R., 2005, in H. U. Käufl, R. Siebenmorgen, & A. F. M. Moorwood (eds.), High Resolution Infrared Spectroscopy in Astronomy, p. 365

Zoccali, M., Renzini, A., Ortolani, S., Greggio, L., Saviane, I., Cassisi, S., Rejkuba, M., Barbuy, B., Rich, R. M., & Bica, E., 2003, A&A 399, 931

James Binney clarifies the final key point in his review.

Nils Ryde presenting his paper.

https://doi.org/10.1017/S1743921308027543 Published online by Cambridge University Press