Carnegie Observatories Astrophysics Series, Vol. 4:
Origin and Evolution of the Elements, 2004
ed. A. McWilliam and M. Rauch (Pasadena: Carnegie Observatories,
http://www.ociw.edu/ociw/symposia/series/symposium4/proceedings.html)

Stellar Abundances in Dwarf Irregular Galaxies

K. A. VENN[1], E. TOLSTOY[2], A. KAUFER[3], and R. P. KUDRITZKI[4]
(1) Macalester College and University of Minnesota, MN, USA
(2) Kapteyn Institute, University of Groningen, Netherlands
(3) European Southern Observatory, Santiago, Chile
(4) Institute for Astronomy, University of Hawaii, HI, USA

Abstract

Dwarf irregular galaxies appear to have undergone very slow chemical evolution since they have low nebular abundances, but have had ongoing star formation over the past 15 Gyr. They are too distant for red giant abundance analyses to examine the details of their chemical evolution, however the isolated, bright blue supergiants do allow us to determine their present-day iron abundances to compare with both stellar and nebular α-element results. The [α/Fe] ratios in four Local Group dwarf irregular galaxies (NGC 6822, WLM, Sextans A, and GR 8) all appear to have solar ratios regardless of the differences in their metallicities and star formation histories. Surprisingly, WLM's stellar metallicity is three times higher than the nebular oxygen abundance. We compare the [α/Fe] ratios in the dwarf irregulars to those from recent analyses of red giant branch stars in dwarf spheroidal galaxies, and also to damped Lyα systems, and discuss these in the context of model predictions.

1.1 Introduction

A examination of the distribution of galaxies in the Local Group (e.g., Figure 3 by Grebel 1999) clearly shows the density-morphology relationship for galaxies. The dwarf spheroidals are all located near the large mass concentrations of the large spirals, with the dwarf irregulars located at greater distances. One of the most useful ways to study the star formation and chemical evolution of a galaxy is to examine the elemental abundances and abundance ratios in its stars. In the Magellanic Clouds and the nearby dwarf spheroidals, it is possible to determine the abundance of a wide range of elements from the red giant branch (RGB) stars, and since these stars have a range of metallicities and ages, then it is possible to build up a picture of the chemical evolution of those galaxies; for more details see the contributions in this proceedings by Hill, Shetrone, and Smith.

The dwarf irregular galaxies appear to have undergone very little and very slow chemical evolution since they have very low nebular abundances (down to 1/20 solar, e.g., Skillman et al. 1989a). If dwarf galaxies are the corner stones for galaxy formation, as in the hierarchical structure simulations in the cold dark matter (CDM) scenarios, then the dwarf irregulars may be the cleanest remnants of the proto-galactic fragments from the high redshift Universe. The dwarf irregular galaxies are too distant for detailed chemical abundance analyses of their RGB stars. However, there are relatively isolated, blue supergiants in these galaxies that are bright enough for detailed spectroscopy using the efficient spectrographs on the new 8 to 10-meter class telescopes. These stars are all young, thus we cannot examine the build-

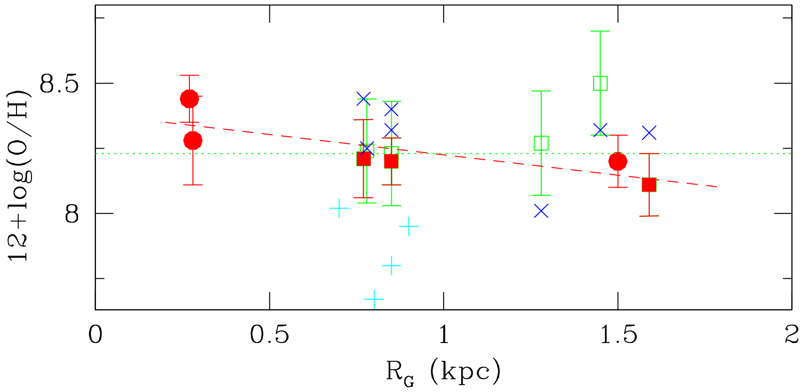

Fig. 1.1. Oxygen abundances versus galactocentric distance in NGC 6822. The results from three A-type supergiants (Venn et al. 2001) are shown by filled circles, and for three nebulae where the O III 4363 line was detected (Pagel et al. 1980) by filled squares. A least squares linear fit to these six (high quality) data points yields a slope that suggests an abundance gradient of –0.1 dex/kpc, which is the same gradient found in the Galaxy over a much larger scale (Smartt & Rolleston 1997). Hollow squares show other nebular data (Pagel et al. 1980); x's note the nebular results when the Pilyugin (2001) R23 calibration is used; +'s note results for two nebulae (Hubble V and X) from other authors. All of the data taken together (of various qualities) is consistent with no slope in the oxygen abundance.

up of elements from these systems as with the RGB stars, but we can examine the abundance of elements not available from nebular analyses (e.g., Fe) to examine the integrated chemical evolution in these systems to the present epoch.

1.2 Stellar Abundances in NGC 6822

The closest, relatively isolated dwarf irregular galaxy is NGC 6822, with $D_{6822} \sim$ 0.5 Mpc. A detailed color-magnitude diagram (CMD) by Gallart et al. (1996a,b) shows that the brightest blue supergiants in this galaxy are nearly 2 magnitudes brighter than the tip of the red giant branch. From Keck-HIRES and VLT-UVES spectroscopy, we showed that two stars located near the center of NGC 6822 have oxygen and iron abundances that are in excellent agreement with the low nebular oxygen abundances (Venn et al. 2001)*; i.e., [O/H] = –0.5 and [Fe/H] = –0.5. Preliminary analysis of a third star is in agreement with these results as well, though this star is located in the outer disk of the galaxy.

An interesting sidelight to these abundances in NGC 6822 is that the stellar and nebular oxygen results may show evidence for an abundance gradient. A marginal detection of a –0.1 dex/kpc gradient can be seen from a least-squares linear fit to the stellar data with the nebular abundances derived only from HII regions where the O III 4363 line is observed; see Fig. 1.1 . This gradient is the same as that seen in the Galactic disk over approximately 20 kpc, or ∼10x larger distance than NGC 6822 (e.g., Smartt & Rolleston 1997). Small scale abundance fluctuations, such as a gradient, are not expected in dwarf galaxies where

* For comparison, solar abundances are from Grevesse & Sauval (1998), except for oxygen, which is adopted as 12+log(O/H) = 8.66 from Asplund (2003, consistent with Allende-Prieto et al. 2001).

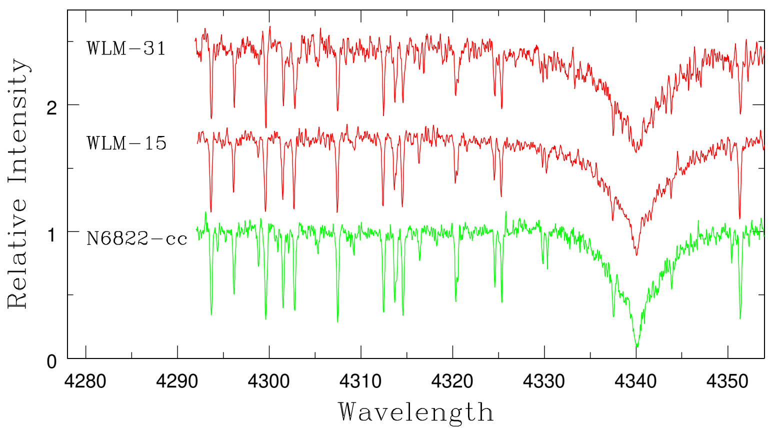

Fig. 1.2. Comparison of VLT+UVES spectra around Hγ for two stars in WLM and one in NGC 6822. All three stars have very similar atmospheric parameters and metallicities.

it is thought that the mixing processes occur on short timescales to throughly mix the interstellar medium. Confirmation of an abundance gradient would suggest much longer mixing timescales, *in general*, for newly processed material from SNe II and massive stars.

1.3 Stellar Abundances in WLM

The dwarf irregular galaxy WLM is more distant than NGC 6822 at $D_{WLM} \sim 1$ Mpc, but it also has lower foreground extinction putting the blue supergiants at similar magnitudes in both of these galaxies. The nebular abundances in WLM are much lower than in NGC 6822 though. Hodge & Miller (1995) and Skillman et al. (1989a) have analyzed three HII regions (totalled); the O III 4363 is detected and the results are in good agreement with one another at [O/H] = −0.9. Thus, this galaxy is about four times *more metal-poor than the SMC*, making it one of the most metal-poor galaxies in the Local Group and suggesting that its chemical evolution has been quite slow.

Spectra of two A-type supergiants were obtained with the VLT+UVES and analyzed using standard techniques (Venn et al. 2003). The stars have [Fe/H] = −0.4, which is nearly 3 σ higher than the nebular oxygen abundance. In fact, this metallicity is in better agreement with the results from NGC 6822, which can be seen directly by comparing a portion of the spectra from the two stars in WLM to a star with similar parameters in NGC 6822 (see Fig. refkvenn3). The WLM stellar oxygen abundance is even higher, [O/H] = −0.2, but this was determined directly from only one star; spectrum synthesis for this one star is shown in Fig. refkvenn2. The radial velocities and stellar parameters do support that these stars are members of WLM. The question then is how can these young stars be more metal-rich than the nebulae?

At present, the most likely scenario is that there are large scale abundance variations in WLM. The two stars are located on the south-east side of the galaxy, whereas the nebular are in the central-west portions. If this is an edge on disk galaxy as suggested by its HI rotation curve (J. Cannon, *private communication*), then their positions within WLM could

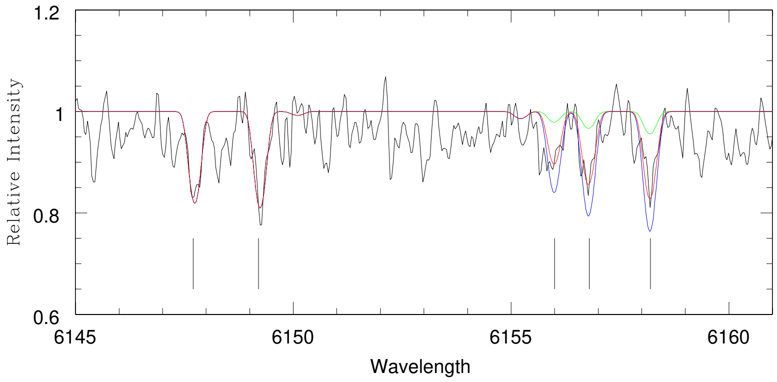

Fig. 1.3. Spectrum synthesis for two Fe II lines, λ6147 and λ6149, and the three O I lines near λ6158 in WLM-15. The best fits to the data are for [Fe/H] = −0.4 and [O/H] = −0.2. The synthesis for an oxygen abundance that is 0.3 dex larger is shown (too large), as well as the nebular oxygen abundance (too small).

be even further apart. However, this galaxy is also significantly smaller than NGC 6822; it has about 1/10 the mass and radius. It would be surprising to find such large abundance variation in WLM and not have seen them in NGC 6822. Other possibilities seem even more unlikely though, e.g, dilution through the recent merger of a large HI cloud (merger would have needed to occur *after* the stars formed only 10 Myr ago), or variations in the interstellar gas-to-dust ratio (such as large amounts of oxygen locked in dust grains). It is not clear yet what the difference in the stellar and nebular abundances are telling us. Is there something peculiar about WLM, or is this result telling us something general about chemical evolution, nucleosynthesis, or abundance measurements?

1.4 The All-Important [α/Fe] Ratio

The evolution of the chemical abundances in a galaxy is intimately linked to its star formation history. Different elements are produced during the evolution of stars of different masses, and over a range of timescales. If the star formation in a galaxy proceeds by a series of bursts, rather than smooth, approximately constant star formation, then this should lead to clear differences in the evolution of the chemical abundances. One ratio of particular importance is the α/Fe ratio, typically characterized by [O/Fe]. Oxygen is produced primarily in the high-mass stars of negligible lifetimes and ejected by SNe II, while iron is produced in both SNe II and SNe Ia. Stars that form shortly after the interstellar medium has been enriched by SNe II may have enriched [α/Fe] ratios, while those that form sometime after the SNe Ia contribute will have lower [α/Fe]. For more details, see the contributions in this proceedings by Matteucci and Chiappini.

Since bursts of star formation allow SNe II to contribute α-elements, and long quiescent periods allow SNe Ia to contribute iron, then the total [α/Fe] ratios in a galaxy should be able to vary over time. Gilmore & Wyse (1991) wrote "*There is nothing special or universal about solar element ratios, and one should not expect* [solar abundances] *in any other environment which has had a different star formation history*". Nevertheless, NGC 6822 has had

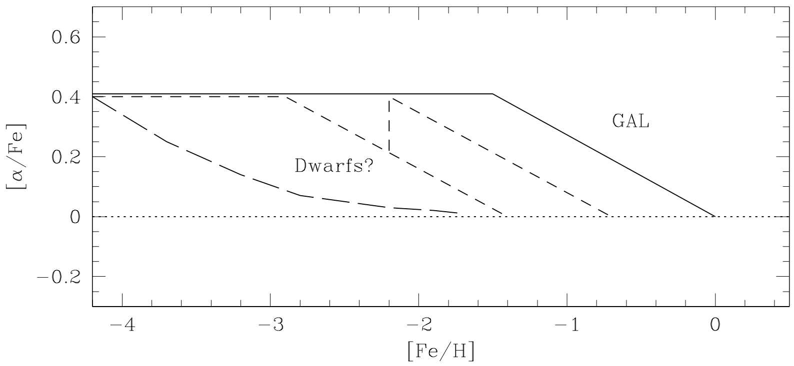

Fig. 1.4. Cartoon of [α/Fe] versus [Fe/H] to illustrate some of the possibilities from different star formation histories and/or different star formation rates. The solid line represents the trend in abundance ratios for Galactic stars. The short dashed lines represent a smaller star formation event where the same peak SNe II [α/Fe] ratio is reached after an initial star formation epoch but at a lower metallicity such that the SNe Ia can contribute significant amounts of iron sooner in the chemical evolution. At some later time, a new burst of star formation might increase [α/Fe] back to the peak SNe II ratio. Alternatively, a very slow star formation rate such as in dwarf galaxies may allow the SNe Ia to contribute at very low metallicities, such that [α/Fe] approaches the solar ratio sooner.

a significantly different star formation history from the solar neighbourhood (see Gallart et al. 1996a,b), and yet its young stars and nebulae have the solar ratio of [O/Fe]. The same is true for the Magellanic Clouds (e.g., Hill 1997, 1999; Hill et al. 1995; Venn 1999; Rolleston et al. 2003). A comparison of the star formation histories for the Magellanic Clouds (e.g., Pagel & Tautvaisiene 1998) and NGC 6822 (Gallart et al. 1996a,b) suggests that NGC 6822 has had almost the opposite star formation history (more old and intermediate-aged stars, few stars forming in the past 5 Gyr, until a recent burst within the past 1 Gyr). How do such different systems result in similar ratios, and why are they all near solar?

Matteucci (2002) had discussed the components that determine galactic evolution and notes that while the star formation history is important in determining absolute abundances at any given time, it is less important when determining abundance ratios. For ratios, the stellar lifetimes, IMF, and nucleosynthesis yields are critical. Thus, galaxies with low star formation rates either in bursts or continuous should show a short plateau in [α/Fe] at low metallcities (irregulars and spirals), whereas galaxies with high star formation rates early in their lifetimes will have longer plateaus (bulges, and ellipticals). A cartoon sketch based on Matteucci's (2002) Figure 1 is shown in Fig. 1.4, where we have also added the potential effects of a strong intermediate-aged burst following Gilmore & Wyse (1991). That all chemical evolution models for all systems tend towards the solar ratio at the present epoch is interesting, and suggests that stellar lifetimes, nucleosynthetic yields, and the IMF, are universal; possibly also that mixing is efficient throughout these galaxies on a relatively short timescale ($\sim$1 Gyr). It is remarkable that any star formation that occurs after the initial epoch seems to have little influence on the present-day ratio, although this may also be

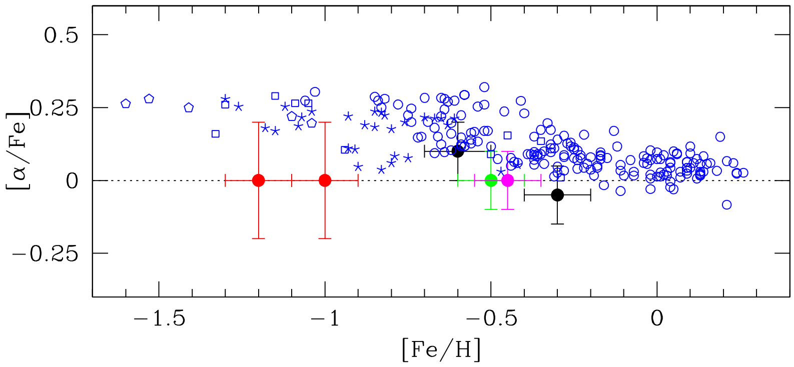

Fig. 1.5. [α/Fe] ratios for young stars in the dwarf irregular galaxies and the Magellanic Clouds, compared to Galactic stars. Filled symbols with error bars are the mean of the young supergiant abundances, in order of increasing metallicity, in Sextans A, GR8, SMC, NGC 6822, WLM, and the LMC (references in text). Two σ errors are plotted for the Sextans A and GR 8 stars because that work is still in progress. Hollow circles represent Galactic data (Edvardsson et al. 1993; Nissen 1997; Stephens 1999; Gratton & Sneden 1988, 1991, 1994; McWilliam et al. 1995).

related to the metallicity having already increased to the point where the addition of new atoms simply doesn't affect the total abundance very much.

This scenario might also help to explain why our preliminary results from two more metal-poor dwarf irregular galaxies, Sextans A and GR 8, also have solar-like [α/Fe] ratios; see Fig. 1.5. Unlike WLM, our preliminary stellar abundances in individual A-type supergiants in Sextans A and GR 8 from VLT+UVES are consistent with the low metallicity determined from their HII regions (Van Zee, Skillman & Hanes 1999; Skillman et al. 1989b) for both oxygen *and* iron. The abundance ratios for WLM and NGC 6822 are taken from the work discussed above. The abundance ratios for the young stars in the LMC and SMC are taken from the literature for B-dwarfs to red giants, which are usually in excellent agreement (e.g., Rolleston et al. 2003; Venn 1999; Hill et al. 1997, 1999; Luck et al. 1998).

We also plot the [α/Fe] ratio in dwarf spheroidal galaxies (Shetrone et al. 2001, 2003) and damped Lyα systems (DLAs, Ledoux et al. 2002); see Fig. 1.6. Again, we see that the ratios are lower than those in the Galactic metal-poor stars in all of these systems. Since the star formation histories are significantly different between each of these systems, e.g., some dwarf spheroidals seem to have formed all of their stars $>$10 Gyr ago (Sculptor), while others have undergone distinct burst of star formation at intermediate ages (Carina), and the dwarf irregulars are still undergoing strong star formation events, then it is impressive that they all have similar low [α/Fe] ratios.

A few systems may show the plateau in the [α/Fe] ratios expected in their metal-poor stars when individual elements are examined; in particular the LMC and Sculptor may show the plateau in [Mg/Fe] in their oldest stars (see the conference contributions by Hill, Shetrone, and Smith in this proceedings).. That [Mg/Fe] may differ from the mean [α/Fe] suggests the

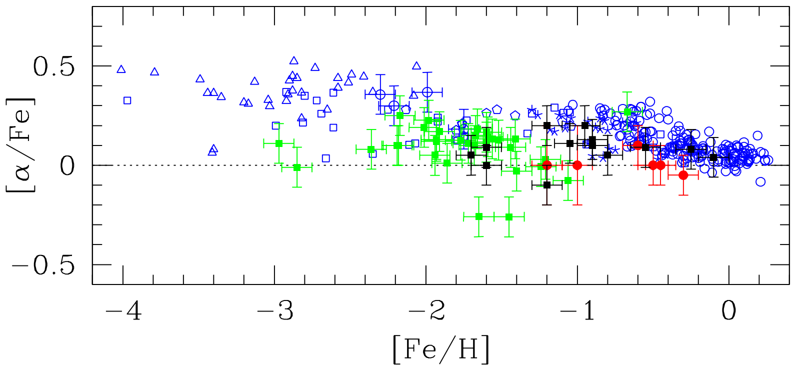

Fig. 1.6. [α/Fe] ratios for stars in the dwarf irregulars (red circles), dwarf spheroidals (green squares), and DLAs (black triangles), compared to Galactic stars. Clearly the [α/Fe] ratio does not reach the peak SNe II contribution in any of these systems. But also, the stars in these systems rarely show subsolar [α/Fe]. See text and Fig. 1.5 for references.

formation of Mg should be considered separately from heavier α-elements such as Ca and Ti. Also, the fact that most stars in the dwarf spheroidals show α-element ratios below the plateau suggests that they all have SNe Ia contributions, thus star formation had to be longer than the timescale for SNe Ia enrichment and mixing into the interstellar medium. Finally, two stars in the dwarf spheroidals do appear to have [α/Fe] that is less than solar. These are Carina-M3 (Shetrone et al. 2003) and Sextans-58 (Shetrone et al. 2001). Tolstoy et al. (2003) estimate the ages for these stars from their red giant position on the CMD; Carina-M3 is 13 $\pm$3 Gyr and Sextans-58 is $\sim$6 Gyr. While ages are not very well constrained, Sextans-58 is the youngest star analyzed in that galaxy which may suggest its chemical evolution has pushed its abundance ratios below the solar value. Carina-M3 is not young though, it is one of the oldest stars analyzed in that galaxy. However, Carina has had a very complex star formation history with at least three distinct star formation epochs. Perhaps the chemical evolution of this galaxy evolved to subsolar ratios before the intermediate-aged burst of star formation raised [α/Fe] again.

1.5 Acknowledgements

Many thanks to Andy McWilliam and Michael Rauch for organizing such a stimulating and interesting conference, also for their generous flexibility in scheduling. KAV would like to thank the NSF for support through a CAREER award, AST-9984073. Also thanks to the Institute of Astronomy, University of Cambridge, for support and hospitality while much of this work has been done.

References

Allende-Prieto C., Lambert D.L., Asplund M., 2001, ApJ, 556, 63
Asplund, M., in CNO in the Universe, ed. C. Charbonnel, D. Schaerer, G. Meynet (San Francisco:ASP), in press
Edvardsson, B., Andersen, J., Gustafsson, B., Lambert, D.L., Nissen, P.E., & Tomkin, J. 1993, A&A, 275, 101
Gallart, C., Aparicio A., Bertelli G., Chiosi C., 1996a, AJ, 112, 1950

Gallart, C., Aparicio A., Bertelli G., Chiosi C., 1996b, AJ, 112, 2596
Gilmore, G., Wyse R.F.G., 1991, ApJ, 367, L55
Gratton, R.G., & Sneden, C. 1988, A&A, 204, 193
Gratton, R.G., & Sneden, C. 1991, A&A, 241, 501
Gratton, R.G., & Sneden, C. 1994, A&A, 287, 927
Grebel E., 1999, in The Stellar Content of the Local Group, IAU Symp. 192, eds. P. Whitelock & R. Cannon (Provo: ASP), 17
Grevesse N., Sauval A.J., 1998, Space Sci. Rev., 85, 161
Hill V., 1999, A&A, 345, 430
Hill V., 1997, A&A, 324, 435
Hill V., Andrievsky, S., Spite, M., 1995, A&A, 293, 347
Hodge, P., Miller B.W., 1995, ApJ, 451, 176
Ledoux C., Bergeron J., Petitjean P., 2002, A&A, 385, 802
Luck R.E., Moffett T.J., Barnes T.G., Gieren W.P., 1998, AJ, 115, 605
Matteucci, F., 2002, to appear in Proceedings of the Evolution of Galaxies III: From Simple Approaches to Self-Consistent Models, astro-ph/0210540
McWilliam, A., Preston, G.W., Sneden, C., & Searle, L. 1995, AJ, 109, 2757
Nissen, P. E., and Schuster, W. J. 1997 A&A, 326, 751
Pagel B.E.J., Edmunds M.G., Smith G., 1980, MNRAS, 193, 219
Pagel B.E.J., Tautvaisienė G., 1998, MNRAS, 299, 535
Pilyugin L.S., 2001, A&A, 374, 412
Rolleston W.R.J., Venn K.A., Tolstoy E., Dufton P.L., 2003, A&A, 400, 21
Shetrone M.D., Côté P., Sargent W.L.W., 2001, ApJ, 548, 592
Shetrone M.D., Venn K.A., Tolstoy E., Primas F., Hill V., Kaufer A., 2003, AJ, 125, 684
Skillman E.D., Kennicutt R.C., Hodge P.W., 1989b, ApJ, 347, 875
Skillman E.D., Terlevich, R., Melnick J., 1989a, MNRAS, 240, 563
Smartt S.J., Rolleston W.R.J., 1997, ApJ, 481, 47
Stephens, A. 1999, AJ, 117, 1771
Tolstoy E., Venn K.A., Shetrone M., Primas F., Hill V., Kaufer, A., Szeifert T., 2003, AJ, 125, 707
Van Zee, L., Skillman E.D., Hanes M.P., 1999, 194th AAS Meeting, 31, 828
Venn, K.A., 1999, ApJ, 518, 405
Venn, K.A., Lennon D.J., Kaufer A., McCarthy J.K., Przybilla N., Kudritzki R.P., Lemke M., Skillman E.D., Smartt S.J., 2001, ApJ, 547, 776
Venn, K.A., Tolstoy E., Kaufer A., Skillman E.D., Clarkson S.M., Smartt S.J., Lennon D.J., Kudritzki R.P., 2003, AJ, 126, 1326