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Planetary nebula abundances in dwarf galaxies

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Abstract. *The framework* of the present review is as follows. The Local Group (LG) is populated by dwarf galaxies belonging to different morphological types. Apparently these galaxies are very different. *The questions* naturally raised from this framework are many. Is there an evolutionary sequence among them? Do they share common progenitors? Is the environment at the origin of their differences? *The method* we propose to answer to these questions is by investigating the chemical evolution of dwarf galaxies and their mass-metallicity relation (MZR). To this aim we use metallicities derived from planetary nebulae, since this stellar population is present in the star-forming (dwarf irregular, dIrr) as well as in the quiescent (dwarf spheroidal, dSph) galaxies. *The results*, actually, show that both dIrr and dSph galaxies of the LG follow the same MZR, at variance with the differences claimed in the past. These results are in good agreement with the recently derived MZR, based on stellar instead of the nebular metallicities of the LG dwarf galaxies. Moreover, our MZR is also consistent with the global MZR of SLOAN star-forming galaxies, which spans a wider stellar mass range ($\sim 10^6$ - 10^{11} $M_\odot$) than the LG dwarfs.

Keywords. ISM: abundances, planetary nebulae; galaxies: dwarf, abundances, evolution.

1. Local Group dwarf galaxies

• The LG dwarf irregular galaxies – dIrrs: are HI-dominated; with variety of irregular shapes. They are found in galaxy clusters, small galaxy groups, and in the field, tending to be isolated. They are also characterised by having almost constant star formation rate (Zhang *et al.* 2012), and old stellar populations have been detected in almost all dIrrs.

• The LG dwarf spheroidal galaxies – dSphs: are dynamically evolved stellar systems; with intermediate to old age stellar populations. These galaxies have mild rotation, and are dominated by dark matter. In the LG, they are typically found close to Andromeda (M31) or to the Milky Way (MW). Though almost devoid of gas in their central parts, some evidence for gas has been found, e.g., in NGC 185 (Gonçalves *et al.* 2012).

• The LG dwarf elliptical galaxies – dEs: they have regular shape and are not completely depleted of gas, being also rotationally supported. In the LG all dEs are located around M31, NGC 205 being the best example (Monaco *et al.* 2009). They pose a mixture of stellar populations and complex star formation histories (Carraro *et al.* 2001).

In terms of total (and HI) mass, the dEs, dSphs and dIrrs have, respectively, $\leqslant 10^8$, $\leqslant 10^5$ and $\leqslant 10^9$ $M_\odot$ ($\leqslant 10^9$, $\sim 10^7$ and $\leqslant 10^{10}$ $M_\odot$) (Carraro 2014).

2. The [morphological] evolution of the [dwarf] galaxies

Kormendy & Djorgovski (1989) proposed an evolutionary relation between the two main morphological types of dwarfs, on which only one type of dwarf galaxy existed when the LG formed, and then the dSphs were formed through the removal of gas in

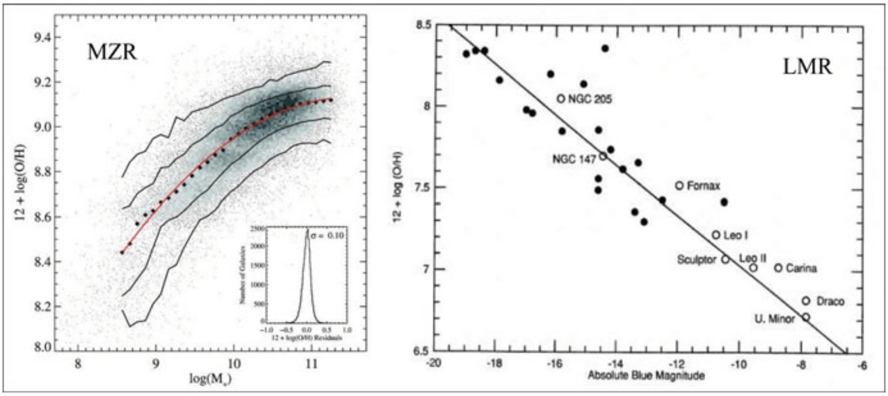

Figure 1. *Left*: Tremonti *et al.* (2004) mass-metallicity relation, on which a tight correlation between M_* and Z is found from the SDSS spectroscopy of 53,000 star-forming galaxies at z 0.1. *Right*: Skillman *et al.* (1989) luminosity-metallicity relation for the dIrrs (filled symbols) and dSphs (empty symbols). For the latter galaxies, the O/H is a conversion from the [Fe/H] derived from the old stellar population.

dIrrs (either via ram-pressure stripping, supernova-driven winds or star formation). More recently Kormendy & Bender (2012) review the morpho-evolution of galaxies in general, not changing significantly this view of dwarfs evolution. Indeed, all dwarfs show signature of old stellar populations, although in different amounts (Weisz *et al.* 2014). These ideas imply that all dwarfs started to form stars at a sharply defined early epoch.

What is the insight the mass-metallicity relation (MZR) could give to the morphological dwarf galaxy evolution? Stellar mass reflects the amount of gas locked up into stars. Metallicity (Z), on the other hand, reflects the gas reprocessed by stars and any exchange of gas between the galaxy and its environment. Tremonti *et al.* (2004) found a tight correlation between stellar mass (M_*) and Z spanning over 3 orders of magnitude in M_* and a factor of 10 in Z, as it can be seen in Fig. 1, adapted from Fig. 6 in Tremonti *et al.* (2004). For this plot, authors considered 53,000 SDSS star-forming galaxies. It is important to also note that the metallicities used in the plot are the oxygen abundances (O/H) derived from the H II regions of the galaxies. The interplay of different effects –star formation efficiency, stellar winds, outflows/inflows and the depth of the potential wells– is responsible for this tight correlation.

A long time ago, in fact back in 1989, Skillman *et al.* (1989) found a clear relation between the O/H and the absolute magnitude of a number of nearby dwarf irregulars. Actually, this paper also shows that the dwarf ellipticals adhere to the same abundance-luminosity relation (LZR) followed by the dIrrs (see the right panel of Fig. 1, which was extracted from Fig. 2 of Skillman *et al.* (1989). These authors pointed out the fact that the relation just discussed could be taken as a support of the 'theory' that dwarf ellipticals are formed by stripping of gas of the dIrrs.

In this scenario, as described by Richer & McCall (1995), once the gas finished and the star formation stopped, the old dwarf irregular-like galaxies fade in luminosity as their stellar population ages. Therefore, dSphs are expected to have, at a given luminosity, higher metallicities than dIrrs.

3. The need of nebular abundances from PNe

The metallicity of the star-forming dIrrs is obtained by measuring the O/H of their H II regions. In dSphs – dominated by the old stellar population – the derived value are

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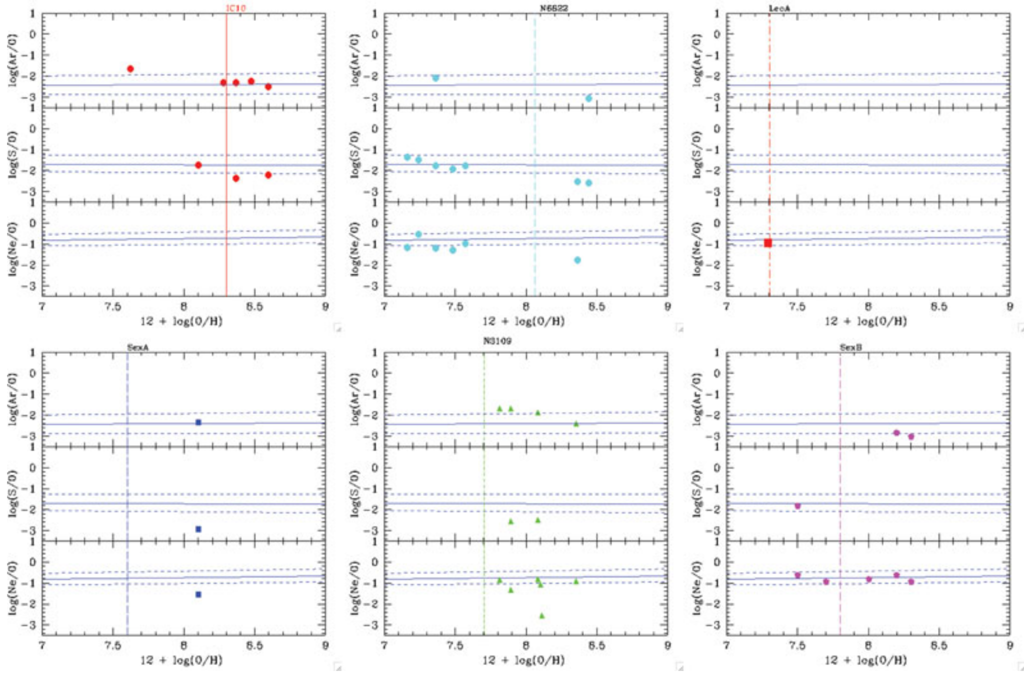

Figure 2. PNe Ne/O, S/O and Ar/O abundance ratios versus oxygen abundance in IC10, NGC 6822, Leo A, Sex A, NGC 3109 and Sex B, nearby dIrrs. Symbols are: red circles for IC10; blue circles for NGC 6822; red box for Leo A; blue box for Sex A; green triangles for NGC 3109; and magenta losangles for Sex B. The quasi-horizontal lines show the abundance line ratios given by the sample H II regions of blue compact galaxies, as compiled by Izotov *et al.* (2006). The vertical lines show the 12 + log(O/H) of the H II regions of each of the dIrr in this plot. These lines are labelled with the corresponding galaxy identification at the top of the plot.

the [Fe/H] from stars. Assumptions about the [O/Fe] are very uncertain, since this ratio depends on the star formation history. Thus, Richer & McCall (1995) proposed the use of metallicities derived from PNe that are present in the star-forming as well as in the quiescent dSph galaxies.

In contrast to H II regions, some elemental abundances in PNe are affected by the nucleosynthesis in the progenitor stars, since newly synthesized material can be dredged-up by convection in the envelope, significantly altering the abundances of He, C and N in the surface layers during the giant branch and asymptotic giant branch (AGB) phases. And, following Kingsburgh & Barlow (1994), Péquignot *et al.* (2000) and Leisy & Dennefeld (2006) a certain amount of oxygen can be mixed in during the thermally pulsing phase of the AGB evolution. However, the dredge-up of O and Ne seems a rare event, happening mainly in low-metallicity environments, therefore we believe that oxygen is a good tracer of the ISM abundances at the epoch of the PN progenitor formation. Various studies have analysed the circumstances that make the dredge-up of oxygen possible, both from theoretical and observational points of view (Siess *et al.* 2004; Magrini *et al.* 2005a; Richer & McCall 2007; Kniazev *et al.* 2005; Peña *et al.* 2007; Kniazev *et al.* 2007, 2008).

In Fig. 2, we study the presence or not of the third-dredge in a number of nearby dwarf irregular galaxies. We do not plot the data for dwarf spheroidal galaxies since the comparison with the present-time ISM is not possible. The idea behind the comparison of PNe abundance ratios as a function of the oxygen abundance in different galaxies,

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with the 12+log(O/H) of the H II regions in each of these galaxies (vertical lines), and in a sample of blue compact galaxies (BCGs, 'horizontal' lines), is that in H II regions, the oxygen that is seen has been produced by the same massive stars that produced the α-process neon, sulphur and argon. Therefore, in these plots, log(Ne/O), log(S/O) and log(Ar/O) should be constant and show no dependence on the oxygen abundance. In fact, inspecting Fig. 2, we see that in the three abundance ratios most of the PNe are distributed along the line that defines the BCGs abundance ratios of H II regions, thus with no trends with respect to the oxygen abundance. The oxygen production in these diagrams should have two effects: (i) to place the PN points well ahead of the mean abundance in the ISM, (ii) to depress the Ne/O, S/O and Ar/O ratios, unless the production of Ne, S and Ar also occurs. In a conservative view, we would expect that the presence of both effects would probe the third-dredge-up of O. Few PNe pass this test full-filling both requests, usually with abundance ratios that are not completely understood. Note, from the plots for galaxies of much lower metallicity, that this contribution is important in the case of Sex A [12+log(O/H) = 7.6] and NGC 3109 [12+log(O/H) = 7.7]. Moreover, the plots in Fig. 2 also give us a lower limit above of which no third dredge-up effect is seen in the nearby dwarf irregulars. We conclude that this limit is around 12+log(O/H) = 7.7 (Magrini & Gonçalves 2009).

4. Dwarf galaxies' luminosity- and mass-metallicity relations

Given the controversial existence of an offset between the LZR of dwarf galaxies, in the sense that for a given luminosity higher metallicities would be found for the dSphs as compared with the dIrrs, we re-analysed the PN LZR and the MZR of the LG dwarfs, in Fig. 3.

To build the LZR the O/H come from our studies and the literature (see the figure caption), whereas the luminosities (M_B) are from Mateo (1998), Lee *et al.* (2003) and van den Bergh (2007). The continuous line shown in Fig. 3 (left panel) gives the weighted least-squares fit to the Z versus luminosity data for the 50 dIrrs within a distance of 5 Mpc, as in van Zee *et al.* (2006). First note that the location of the dIrrs and dSphs in the LZR cannot be clearly separated from each other, meaning that the offset we found previously (see Richer & McCall 1995 and Gonçalves *et al.* 2007) has vanished. This is so because in the present version of the plot we use new (and more accurate) measurements of PN metallicities. Coherently, this is in agreement with the latest results from the spectroscopically determined stellar LZR (Kirby *et al.* 2013).

As discussed in the previous section, O was produced, and brought to the surface of the central stars via the third dredge-up in a few PNe of the dIrrs Sex A (Magrini *et al.* 2005) and NGC 3109 (Peña *et al.* 2007). Judging from Fig. 3, the presence or not of these two galaxies would not change the LZR significantly. Following Kniazev *et al.* (2007), the self-production of O occurred in the Fornax. A lower 12+log(O/H), by 0.27±0.10, was proposed by these authors in order to reconcile the galaxy abundance patterns of S/O, Ne/O and Ar/O with the expected values. The other discrepant dwarf in the relation is Sgr, whose contamination via accretion of enriched gas expelled by our Galaxy could better explain its PNe O/H (Zijlstra *et al.* (2006).

The mass-metallicity relation (MZR) of the LG dwarf galaxies is given in the right panel of Fig. 3. We note that, as in the case of the LZR, dIrrs and dSphs are not segregated, and follow a common relation. In this figure we plot the least-squares fit obtained by Kirby *et al.* (2013, see their eq. 4) using the stellar metallicities in dwarf galaxies and our least mean square fit (see Gonçalves & Magrini 2014 for the details of the conversion). The lowest mass in Kirby's *et al.* (2013) was of the order of $10^3 M_\odot$. In Fig. 3, we encompass a

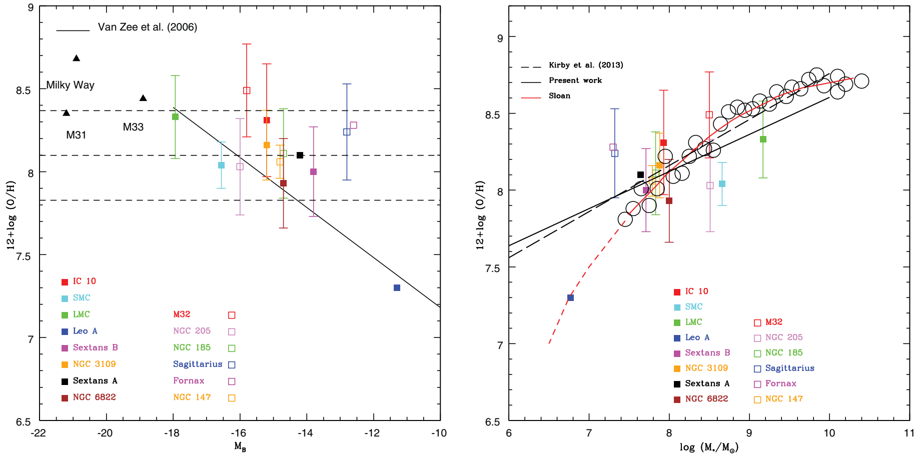

Figure 3. *Left*: The PNe LZR of the LG dwarf galaxies, showing 12+log(O/H) vs. magnitude. Filled symbols represent the dIrrs while the dSphs are have empty symbols. The continuous line represents the LZR, from H II regions of nearby (D $\leqslant$ 5 Mpc) galaxies with magnitudes fainter than -18 (van Zee *et al.*, 2006). The dashed lines represent the mean value and standard deviation (8.098±0.27) for the PNe of all the dwarf galaxies in the plot. For 12+log(O/H): IC 10, Magrini & Gonçalves (2009); SMC, Shaw *et al.* (2010); LMC, Leisy & Dennefeld (2006); Sextans A and Sextans B, Magrini *et al.* (2005); Leo A, van Zee *et al.* (2006); NGC 3109, Peña *et al.* (2007); NGC 6822, Hernández-Martinez *et al.* (2009); M32, RM08; NGC 205, Richer & McCall (2008) plus Gonçalves & Magrini (2014); NGC 185, Gonçalves *et al.* (2012); Sagittarius, Zijlstra *et al.* (2006) and Otsuka *et al.* (2011); Fornax, Kniazev *et al.* (2007); and NGC 147, Gonçalves *et al.* (2007); M31, Jacoby & Ciardullo (1999), Kwitter *et al.* (2012), Balick *et al.* (2013); Milky Way, Perinotto *et al.* (2004); M33, Magrini *et al.* (2009). Dwarf galaxies luminosities (M_B) are from Mateo (1998), those for the LMC and SMC are from Lee *et al.* (2003). M_B of the Galaxy, M31 and M33 are from van den Bergh (2007). *Right*: The PN MZR of the LG dwarf galaxies, showing 12+log(O/H) vs. stellar mass. Symbols and references are as in the left panel. Data for stellar masses were taken from the compilation by McConnachie (2012). The dashed line represents the mass-stellar metallicity relation of Kirby *et al.* (2013) to which we added a constant to match the oxygen metallicity, while the continuous line is the mean least square fit to our data. The direct method mass-metallicity relation for $M_\star$ stacks in Sloan SDSS Data Release 7 (DR7; Abazajian *et al.* 2009) (empty circles) from Andrews & Martini (2013). The red solid curve shows the asymptotic logarithmic fit to the direct method measurements. The dashed red curve is an extrapolation of the fit.

smaller stellar mass range ($10^7 M_\odot$ to $10^9 M_\odot$) in which we find that the MZR has a slope similar to that of the relation built with stellar metallicities. The MZR with O/H seems to deviate only when reaching the stellar mass of the dIrr Leo A with $M_\star < 10^7 M_\odot$.

Fig. 3 also includes the comparison with the MZR for $M_\star$ stacks, obtained with Sloan SDSS Data (Andrews & Martini 2013). Oxygen abundances are obtained adopting the direct method, since the [O III], [O II], [N II], and [S II] electron temperatures are measured from the stacked spectra – of ∼200,000 star-forming galaxies in bins of 0.1 dex in stellar mass. Thus, Andrews & Martini (2013)'s MZR is easily comparable with our results.

The above results point out a *possible* universality of the MZR for both dIrr and dSph galaxies. At variance with the previous results (see Richer & McCall 1995; Gonçalves *et al.* 2007), which indicated a clearly different behaviour of dIrrs and dSphs, now these two classes of galaxies are compatible with a *unique mass-metallicity relation*. It is interesting to notice that both dIrrs and dSphs are consistent with global MZR of star forming galaxies, likely because chemical evolution is a function of stellar mass and its correlation with the total mass (baryonic and non-baryonic) of the galaxy.

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References

Amari, S., Hoppe, P., Zinner, E., & Lewis R. S. 1995, *Meteoritics*, 30, 490
Abazajian, K. N., Adelman-McCarthy, J. K., Agüeros, M. A., Allam, S. S., & Allende-Prieto, C., *et al.* 2009, *ApJS*, 182, 543
Andrews, B. H. & Martini, P. 2013, *ApJ*, 765, 140
Balick, B., Kwitter, K. B., Corradi, R. L. M., & Henry, R. B. C. 2013, *ApJ*, 774, 3
Gonçalves, D. R., Magrini, L., Leisy, P., & Corradi, R. L. M. 2007, *MNRAS*, 375, 715
Gonçalves, D. R., Magrini, L., Martins, L. P., Teodorescu, A. M., & Quireza, C. 2012, *MNRAS*, 419, 854
Gonçalves, Denise R., Magrini, Laura, Teodorescu, Ana M., & Carneiro, Carolina M. 2014, *MNRAS*, 444, 1705
Grebel, E. K., Gallagher, J. S., III, & Harbeck, D. 2003 *AJ*, 125, 1926
Hernández-Martínez, L., Peña, M., Carigi, L., & García-Rojas, J. 2009, *A&A*, 505, 1027
Jacoby, G. H. & Ciardullo, R. 1999, *ApJ*, 515, 169
Kingsburgh, R. L. & Barlow, M. J. 1994, *MNRAS*, 271, 257
Kirby, E. N., Cohen, J. G., Guhathakurta, P., Cheng, L., Bullock, J. S., & Gallazzi, A. 2013, *ApJ*, 779, 102
Kniazev, A. Y., Grebel, E. K., Pustilnik, S. A., Pramskij, A. G., & Zucker, D. B. 2005, *AJ*, 130, 1558
Kniazev, A. Y., Grebel, E. K., Pustilnik, S. A., & Pramskij, A. G. 2007, *A&A*, 468, 121
Kormendy, J. & Djorgovski, S. 1989, *ARA&A*, 27, 235
Kormendy, J. & Bender, R. 2012, *ApJS*, 198,2
Kwitter, K. B., Lehman, E. M. M., Balick, B., & Henry, R. B. C. 2012, *ApJ*, 753, 12
Lee, H., McCall, M. L., Kingsburgh, R. L., Ross, R., & Stevenson, C. C. 2003, *AJ*, 125, 146
Leisy, P., Dennefeld, M. 2006, *A&A*, 456, 451
McConnachie, A. W., 2012 *AJ*, 144, 4
Magrini, L., Leisy, P., Corradi, R. L. M., Perinotto, M., Mampaso, A., & Vilchez, J. M. 2005, *A&A*, 443, 115
Magrini, L., Leisy, P., Corradi, R. L. M., Perinotto, M., Mampaso, A., & Vilchez, J. M. 2005, *A&A*, 443, 115
Magrini, L. & Gonçalves, D. R. 2009, *MNRAS*, 398, 280
Magrini, L., Stanghellini, L., & Villaver, E. 2009, *ApJ*, 696, 729
Mateo, M. L. 1998, *ARA&A*, 36, 435
Otsuka, M., Meixner, M., Riebel, D., Hyung, S., Tajitsu, A., & Izumiura, H. 2011, *ApJ*, 729, 39
Peña, M., Stasińska, G., & Richer, M. G. 2007, *A&A*, 476, 745
Perinotto, M., Morbidelli, L., & Scatarzi, A. 2004, *MNRAS*, 349, 793
Péquignot, D., Walsh, J. R., Zijlstra, A. A., & Dudziak, G. 2000, *A&A*, 361, L1
Richer, M. G. & McCall, M. L. 1995, *ApJ*, 445, 642
Richer, M. G. & McCall, M. L. 2007, *ApJ*, 658,328
Richer, M. G. & McCall, M. L. 2008, *ApJ*, 684, 119
Salaris, M. & Girardi, L. 2005, *MNRAS*, 357, 669
Shaw, R. A., Lee, T.-H., Stanghellini, L., Davies, J. E., García-Hernández, D. A., *et al.* 2010, *ApJ*, 717, 562
Skillman, E. D., Kennicutt, R. C., & Hodge, P. W. 1989, *ApJ*, 347, 875
Tremonti, C. A., Heckman, T. M., Kauffmann, G., Brinchmann, J., Charlot, S., *et al.* 2004, *ApJ*, 613, 898
Weisz, Daniel R., Dolphin, Andrew E., Skillman, Evan D., Holtzman, Jon, Gilbert, Karoline M., Dalcanton, Julianne J., & Williams, Benjamin F. 2014, *ApJ*, 789, 147
van den Bergh, S., 2007, in *The Galaxies of the Local Group*, Cambridge: Cambridge University Press 2007
van Zee, L., Skillman, E. D., & Haynes, M. P. 2006, *ApJ*, 637, 269
Zijlstra, A. A., Gesicki, K., Walsh, J. R., Péquignot, D., van Hoof, P. A. M., & Minniti, D. 2006, *MNRAS*, 369, 875