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Red supergiants as cosmic abundance probes

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Abstract. Accurate chemical abundance information provides a powerful diagnostic of a galaxy's formation and star-forming history. However, obtaining such information is extremely challenging, and it has been shown recently that abundances derived from the spectra of HII regions are highly uncertain. Here we present a new method of extracting a galaxy's chemical abundances from the spectra of their brightest stars, the Red Supergiants. This technique operates at low spectral resolution, and so in combination with the latest instrumentation (e.g. KMOS) can measure abundances of single stars out to distances of 4Mpc. In these proceedings we present verification of our technique on RSGs in the Milky Way, LMC and SMC. We also describe how this method also works on young stellar clusters at distances of up to 40Mpc, which we will demonstrate with our pilot study of a cluster in M83.

Key words. Stars: abundances – Stars: atmospheres – Stars: supergiants – Galaxy: abundances – Cosmology: observations

1. Introduction

The observed relationship between a galaxy's stellar mass and its central metallicity, as well as the abundance trends as a function of galactocentric distance in spiral galaxies, have provided vital clues as to how galaxies form and evolve both in the local universe (e.g. Zaritsky et al. 1994; Garnett 2002) and at larger redshift (e.g. Tremonti et al. 2004; Maiolino et al. 2008). These observations have been used to test the theoretical predictions of various aspects of galaxy formation and evolution under the framework of a dark energy and cold dark matter dominated universe, such as hierarchi-

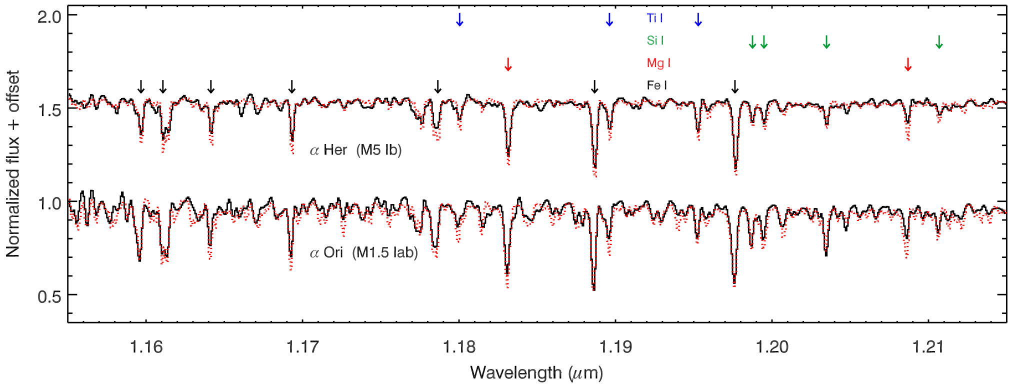

Fig. 1. *J*-band spectra of two Galactic RSGs, at a resolution of roughly R = 5000. Note that the molecular lines that dominate most regions of the optical/NIR spectra of RSGs are largely absent in this spectral window, with the dominant features being atomic lines of Fe, Si, Mg and Ti. Taken from Davies et al. (2010).

cal clustering, infall, galactic winds and variations in the stellar Initial Mass Function (IMF) (De Lucia et al. 2004; Köppen et al. 2007, plus many others).

However, there are several known problems with existing methods to determine chemical abundances. Firstly, the published results, which rely on observations of strong HII-region emission lines, are highly uncertain. It has recently been shown that both the mass-metallicity relationship and the metallicity gradients of spiral galaxies are heavily dependent on the calibration used (Kewley & Ellison 2008; Bresolin et al. 2009).

2. Red supergiants as abundance probes

To address the problem of accurate metallicities for galaxies, we have developed a new technique with which to study the abundances and abundance gradients of galaxies – using individual Red Supergiants as metallicity probes. These stars are extremely bright, up to $\sim 10^{5.7} L_{\odot}$, with flux distributions which peak in the near-infrared (NIR), meaning that they can easily be picked out at large (extra-galactic) distances and regions of high extinction.

Determining chemical abundances from these objects has typically required high-resolution spectroscopy to resolve out the diagnostic metal lines from the large number of molecular transitions. At a resolution of $R \approx 20,000$, this places a limiting distance on such observations with an 8m telescope of ~1Mpc – fine for Galactic work (e.g. Davies et al. 2009a,b), but no good for extragalactic studies.

However, there is a spectral window at ~1.2μm where the molecular lines are very weak and relatively few in number, and instead the dominant features are strong atomic lines of Fe, Si, Mg and Ti (Davies et al. 2010, see Fig. 1). These lines can be used to determine direct elemental abundances, as opposed to measuring the abundance of a single element and using this as a proxy for the abundances of all metals (e.g. O in HII-region studies).

Since the contribution of molecular lines in this spectral window is negligible, the resolution can be lowered by a factor of ~10, and we therefore increase the limiting distance by $\sqrt{10}$. At resolutions of ~3000, we can also take advantage of multi-object spectrographs such as the VLT's KMOS, meaning that in a single night it is now possible to map the abundances of entire galaxies at distances of 4Mpc – a volume containing roughly 100 star-forming galaxies.

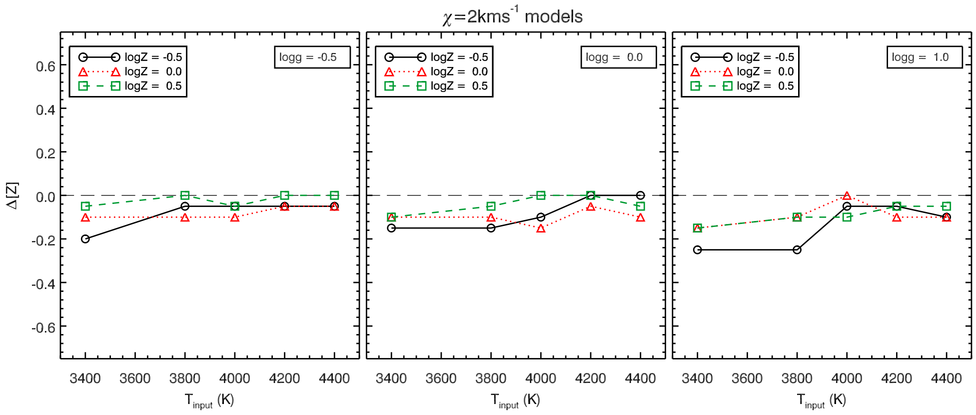

Fig. 2. The difference between the measured abundances ΔZ when one analyses input spectra using models which assume LTE, and those which incorporate non-LTE corrections. Though corrections are small – typically <0.2dex – they are significant as they are comparable to the absolute measurement uncertainties. Taken from Bergemann et al. (2013).

3. Models and observations

We have calculated a grid of ~2000 MARCS model atmospheres covering the parameter space of RSGs, and metallcities from $-1.5 < [Z] < +1.0$. These models are computed under the assumptions of spherical symmetry, hydrostatic equilibrium and local thermodynamic equilibrium (LTE) (Gustafsson et al. 2008). For our diagnostic lines in the J-band however, we have computed non-LTE corrections (Bergemann et al. 2012a, 2013). These corrections are on average small, but significant compared to the absolute errors on abundance measurements (≲0.2dex, see Fig. 2).

Initially, we have begun our study by analysing the three nearest galaxies – our own, and the two Magellanic Clouds. These environments have been subjected to numerous abundance studies, and allow us to throroughly road-test our technique against a variety of others. In Davies et al. (2010) we analysed archival IRTF/SpeX spectra of a sample of Galactic RSGs, finding results consistent with Solar ($[Z] = 0.13 \pm 0.14$). We will also shortly present a study the RSGs of Per OB1, and a comparison with a similarly detailed analysis of the Blue Supergiants in that association (Gazak et al., in prep). In addition, we have obtained spectra of samples of RSGs in both the Large and Small Magellanic Clouds using VLT/XSHOOTER. Analysis of these stars reveals abundances which are consistent with those obtained from other young-age abundance tracers (e.g. Trundle et al. 2007).

The next step will be to push out to nearby galaxies, such as NGC 300, for which again a number of different abundance studies exist (Kudritzki et al. 2008; Bresolin et al. 2009).

4. Abundances from massive clusters of RSGs

When a star cluster of initial mass ~ $10^5 M_\odot$ reaches an age of ~6Myr, the most massive remaining stars are of sufficiently low mass (~$30 M_\odot$) to enter the RSG phase. At this point a cluster of this mass will produce up to 100 RSGs. Known examples of such clusters, albeit with slightly lower masses, are NGC 7419, and the RSGCs in the region of Scutum tangent (e.g. Caron et al. 2003; Figer et al. 2006; Davies et al. 2007; Clark et al. 2009).

Once RSGs begin to appear they dominate the integrated light in the NIR (Gazak et al. 2013, see Fig. 3). Since RSGs at a given metallicity all have roughly the same spectral appearance in the J-band (Davies et al. 2010), the spectrum of an unresolved massive, young star cluster will look basically the same as that of an individual RSG, only ~100× brighter.

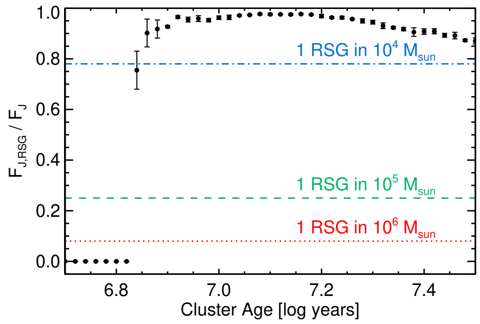

Fig. 3. The percentage contribution of RSGs to the integrated J-band flux of a massive star cluster, as a function of the cluster age. These numbers are calculated from population synthesis using Geneva evolutionary tracks (Meynet & Maeder 2000) and a Salpeter initial mass function. See Gazak et al. (2013) for details.

This then means that we can obtain accurate abundances for such clusters out to distances a factor of 10 greater than for individual stars. We have recently obtained spectra of two such clusters in nearby galaxies, and will demonstrate this technique in forthcoming papers.

5. The future: potential with ELTs

Clearly, there is enormous potential for resolved stellar population studies in the ELT era, in particular in the NIR where the optimal adaptive optics correction is obtained. To determine precisely the benefits for our J-band technique in the ELT era we ran experiments using instrument simulators and PSF synthesis calculations (Evans et al. 2011). We began with template spectra with known metallicities, and simulated the corresponding observed spectra for a range of specified output magnitudes. We then ran our analysis routines on the output spectra, to determine the point at which the measured metallicity begins to substantially depart from that of the input. We found that random errors in excess of 0.2dex began to appear at simulated magnitudes of $J \sim 23$. For a typical RSG absolute magnitude of $M_J = -11$, this corresponds to an impressive distance of 70Mpc, a substantial fraction of the local Universe containing entire clusters of galaxies.

References

Bergemann, M., Kudritzki, R.-P., Plez, B., et al. 2012a, ApJ, 751, 156
Bergemann, M., Kudritzki, R.-P., Wueurl, M., et al. 2013, ApJ, 764, 115
Bresolin, F., Gieren, W., Kudritzki, R., et al. 2009, ApJ, 700, 309
Caron, G., et al. 2003, AJ, 126, 1415
Clark, J. S., Negueruela, I., Davies, B., et al. 2009, A&A, 498, 109
Davies, B., Figer, D. F., Kudritzki, R.-P., et al. 2007, ApJ, 671, 781
Davies, B., Kudritzki, R., & Figer, D. F. 2010, MNRAS, 407, 1203
Davies, B., Origlia, L., Kudritzki, R., et al. 2009a, ApJ, 694, 46
Davies, B., Origlia, L., Kudritzki, R., et al. 2009b, ApJ, 696, 2014
De Lucia, G., Kauffmann, G., & White, S. D. M. 2004, MNRAS, 349, 1101
Evans, C. J., Davies, B., Kudritzki, R.-P., et al. 2011, A&A, 527, A50
Figer, D. F., MacKenty, J. W., Robberto, M., et al. 2006, ApJ, 643, 1166
Garnett, D. R. 2002, ApJ, 581, 1019
Gazak, J. Z., Bastian, N., Kudritzki, R. P., et al. 2013, MNRAS, 430, L35
Gustafsson, B., Edvardsson, B., Eriksson, K., et al. 2008, A&A, 486, 951
Kewley, L. J. & Ellison, S. L. 2008, ApJ, 681, 1183
Köppen, J., Weidner, C., & Kroupa, P. 2007, MNRAS, 375, 673
Kudritzki, R., Urbaneja, M. A., Bresolin, F., et al. 2008, ApJ, 681, 269
Maiolino, R., Nagao, T., Grazian, A., et al. 2008, A&A, 488, 463
Meynet, G. & Maeder, A. 2000, A&A, 361, 101
Tremonti, C. A., Heckman, T. M., Kauffmann, G., et al. 2004, ApJ, 613, 898
Trundle, C., Dufton, P. L., Hunter, I., et al. 2007, A&A, 471, 625
Zaritsky, D., Kennicutt, Jr., R. C., & Huchra, J. P. 1994, ApJ, 420, 87