RevMexAA (Serie de Conferencias), **16**, 145–149 (2003)

Science with the GTC 10-m Telescope (Granada, España, 5-8 febrero 2002)
Editors: José Miguel Rodríguez Espinosa, Francisco Garzón López & Verónica Melo Marín

STELLAR ASTROPHYSICS IN THE LOCAL GROUP AND BEYOND WITH THE GTC

Stephen J. Smartt

Institute of Astronomy, Cambridge, UK

RESUMEN

En lo que sigue discutiré las capacidades que el GTC y en particular OSIRIS aportarán al estudio de las poblaciones estelares de estrellas masivas de las galaxias del Grupo Local y más allá. La observación de estrellas masivas en galaxias irregulares enanas así como en espirales permite estudiar la evolución y formación estelar en entornos extremos, o las propiedades de los vientos estelares de estrellas masivas luminosas. Esto a su vez contribuirá a la determinación de distancias con precisiones del orden del 10%.

ABSTRACT

In this review I discuss the capabilities that the GTC, and in particular the OSIRIS spectrometer, will bring to studying massive stellar populations within Local Group galaxies and even beyond. By observing massive stars in other dwarf irregular and spiral galaxies one can probe star formation and stellar evolution in extreme environments, the wind properties of massive luminous stars, and determine distances to an accuracy of ∼10%.

Key Words: **STARS:ABUNDANCES — STARS: EARLY-TYPE — STARS : EVOLUTION — STARS: WOLF–RAYET — STARS:WINDS**

1. INTRODUCTION

The multiobject spectrograph OSIRIS will not support particularly high resolution spectroscopy, its highest mode being $R \sim 2500$ with a $0.6''$ slit. Although this may limit what it can achieve in some areas of stellar astrophysics, it can still support a range of research based broadly around observing the most massive luminous stars in external galaxies. Recent projects on 8 m telescopes with similar performance spectrometers (VLT + FORS and Gemini + GMOS) has already shown this potential (e.g., Bresolin et al. 2001, 2002)

2. BLUE SUPERGIANTS IN SPIRALS AND IRREGULAR GALAXIES

After the end of H-burning on the main sequence, massive O-type main sequence stars (of typically $M_* > 20M_\odot$) evolve across the HR diagram to become blue supergiants. They have luminosities of up to $10^6\ L_\odot$ and absolute visual magnitudes dependent on their effective temperatures, but typically $-9 < M_V < -6$. During the B–A–F-type spectral region, they are the *visually* brightest, blue, single stars in external galaxies. In Local Group star forming galaxies (within ∼1 Mpc they have $V \sim 16$–19^m, hence can be observed spectroscopically at medium–high resolution with 8–10 m telescopes. The highest resolution mode of OSIRIS is provides a $FWHM \sim 120$ km s^{-1}, which is larger than the intrinsic line widths of the B–A–F-type supergiants (50–100 km s^{-1}). Bresolin et al. (2001) have shown that spectral synthesis of reasonably high signal-to-noise data can determine stellar parameters and an *overall* stellar metallicity. The optical spectra of blue supergiants contain absorption lines due to He, C, N, O, Mg, Si, S, Ca, Sc, Ti, Cr, Mn, Fe, Ni, Sr, Zr, and Ba, and hence the potential exists to determine the abundances of these elements throughout the Local Group. However, the resolution limitation of OSIRIS means that it is not the ideal instrument to determine fine line abundances in these stars. Other instruments (such as EIS/HIRES/DEIMOS on Keck, FLAMES on the VLT) will be better suited to this. But OSIRIS can complement and add to the area as described below.

While oxygen abundances have been measured through emission line nebula in all the Local Group dwarf irregulars (Skillman, Kennicutt, & Hodge 1989), their iron content is almost unknown. If they behave like the Magellanic Clouds, then the [O/Fe] ratios will be zero, however if they are like the metal poor stars in our own Milky Way they will have significantly different Fe abundances. It is thought that the abundance of Fe (and the other Fe-group elements such as Ni) is a key parameter in the driving of stellar winds through radiation pressure as it is the dominant source of line opacity. And as mass loss is crucial in the evolution of high mass stars, one would

Science with the GTC 10-m Telescope (Granada, España, 5-8 febrero 2002)
Editors: José Miguel Rodríguez Espinosa, Francisco Garzón López & Verónica Melo Martín

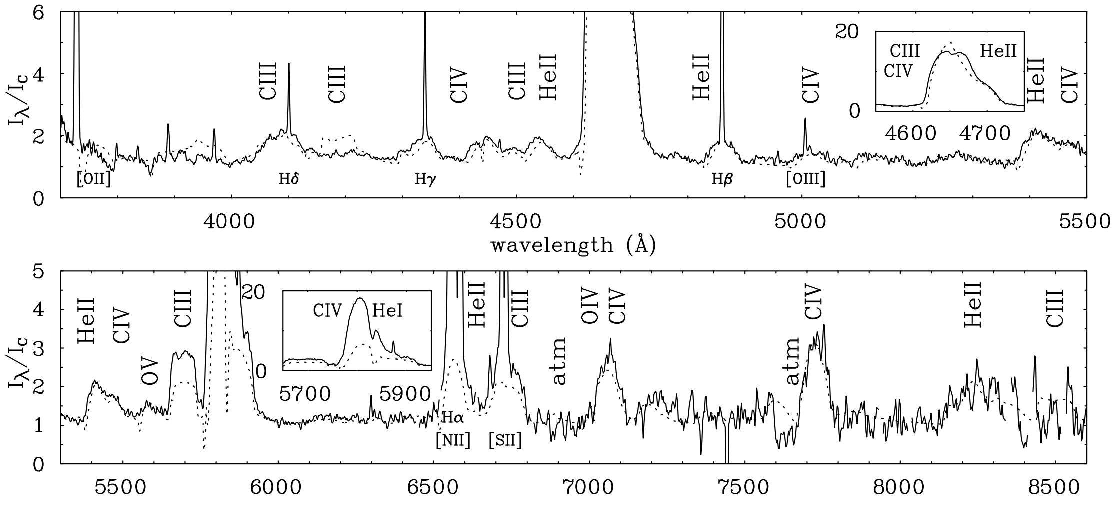

Fig. 1. Figure taken from Smartt et al. (2001), showing a comparison between rectified WHT/ISIS spectroscopy of the Wolf–Rayet star M31-OB 10-WR1 (solid) and a synthetic model (dotted). This star is a WC6 star in the nearby spiral galaxy M31, and this figure shows that even with a 4 m telescope in only 0.5 hr exposure, excellent quality spectra can achieved owing to the strong emission lines of these stars. Low–medium resolution is adequate for the analysis of WR stars because of the width of the emission features, and this case was ∼4 Å. With OSIRIS and GTC one could observe these stars within approximately 10 Mpc of the Milky Way.

like to compare massive stellar evolution in environments with known Fe abundances. The Fe abundances can be determined in dwarf irregular galaxies such as WLM, NGC 6822, IC 1613, GR8, IC 10 through high resolution single object spectroscopy of the A–F type supergiants (the measurement is not easily achieved with H II regions; Venn et al. 2001). The GTC and OSIRIS can then used to determine parameters of the massive stellar population such as the initial mass function (IMF), the ratio of red–blue supergiants, the mass loss rates and wind momenta of blue supergiants, the relative numbers of Wolf–Rayet stars and their various subtypes.

3. THE INITIAL MASS FUNCTION AND BLUE–RED SUPERGIANT RATIO

Extensive efforts over the last decade have determined the IMF in the upper regions of the HR diagram in a variety of environments within the Local Group (e.g., Massey et al. 1995a,b and references therein). These range from the metal poor clusters and field of the SMC and LMC to the metal-rich inner regions of the spiral galaxies M31 and M33. There appears to be little difference in the IMF across this large range in metallicity—from $Z_\odot$ to $0.2Z_\odot$ (in the SMC). Hence it would appear that star formation proceeds fairly independently of metallicity, although there is some evidence of a steeper slope in the field of the SMC than in clusters. These studies rely on accurate spectral typing and conversion to luminosity and mass through atmospheric and evolutionary models and have been carried out with 2–4 m telescopes. However with GTC and OSIRIS, one could extend these studies to much lower metallicity environments. Within 1–2 Mpc, there are several star forming galaxies with metallicities much lower than that of the SMC (see Skillman et al. 1989), such as IC 1616, WLM, Sex A, Leo A and GR8. The lowest of these (GR8 and Leo A) have $12 + \log \mathrm{O/H} \simeq 7.4$, or just 5% of solar. Hence looking at the IMF in the upper regions of the HR diagram in these galaxies is the closest we can get to resolved stellar populations that might resemble those of the first stars formed in the Universe. Massey (1998) has discussed taking spectra of the most massive luminous stars as being essential in determining an accurate IMF, since the photometric colors of hot blue stars become degenerate at spectral types earlier than ∼B2. Hence taking spectra of objects with magnitudes between $B \simeq 19$–21^m is essential—and well within the capabilities of GTC + OSIRIS.

As well as looking at the IMF in these very metal-poor regions, one could also probe the blue–red supergiant ratio. This ratio has been measured in the

Science with the GTC 10-m Telescope (Granada, España, 5-8 febrero 2002)
Editors: José Miguel Rodríguez Espinosa, Francisco Garzón López & Verónica Melo Marín

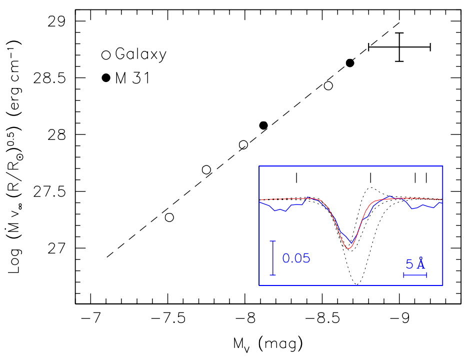

Fig. 2. Figure taken from Bresolin et al. (2001), illustrating the use of 8 m telescopes in exploiting the wind momentum–luminosity relationship. In this figure, the the modified wind momentum is plotted against luminosity, expressed here in terms of absolute V magnitude for A-type supergiants in the Galaxy (open circles) and M31 (filled circles). The point with the error bar is an A-type supergiant in NGC 3621 at a distance of 6.7 Mpc. The inset shows how the mass loss rate was estimated by means of Hβ line profile fits with non-LTE unified wind model atmospheres, including stellar winds. The stellar spectra were taken with FORS on the VLT, with a total exposure time of 10.7 hr and spectral resolution of 5 Å. This example star has a magnitude of $V = 20.47$.

Galaxy and Magellanic Clouds and appears to be very strongly dependent on metallicity; e.g., Eggenberger et al. (2002), and Table 1. The measurement of this ratio is fundamental in constraining models of massive stellar evolution. The relative lifetimes of blue and red supergiants are very sensitive to mass loss, convection, and mixing processes in the models, and hence varying these can lead to differing predictions for the B/R ratio. Beyond basic stellar astrophysics, this has important implications for supernova and GRB progenitors, and synthesizing stellar populations in unresolved galaxies. So far evolutionary modelers have been able to reproduce the B/R ratio at any particular metallicity by adjusting various parameters in the input to the models—but, crucially *are not able to consistently reproduce its dependence on metallicity*. Eggenberger et al. (2002) conclude, 'The problem of the blue to red supergiant ratio (B/R ratio) remains one of the most severe problems in stellar evolution'. Table 1 lists the B/R measured ratios as a function of metallicity. However at metallicities below the SMC the ratio is not well quantified. By observing the B/R ratio in the galaxies listed above with GTC + OSIRIS, one could constrain this further and importantly into the metallicity regime applicable for the early Universe.

TABLE 1

THE BLUE–RED SUPERGIANT RATIO BY NUMBER AS A FUNCTION OF METALLICITY. THIS HAS NOT BEEN PROBED WELL BELOW SMC METALLICITIES, AND GTC + OSIRIS CAN ENHANCE THIS AREA.

Region	$Z/Z_\odot$	B/R ratio
Inner MW	1.5	50
Solar neighborhood	1	30
Outer MW	0.6	15
LMC	0.5	10
SMC	0.2	4
Below SMC	0.05	?

4. MASSIVE STELLAR EVOLUTION

In addition to determining the B/R ratio in low metallicity galaxies, a further important constraint on massive stellar evolution is the relative numbers of the Wolf–Rayet subtypes. Powerful diagnostics are WC/WN, WR/O-stars and WR/red-supergiant numbers. One does not need particularly high spectral resolution to determine these ratios. As shown in Smartt et al. (2001), Crowther et al. (2002), and Bresolin et al. (2002), detailed model atmosphere and wind analyses of WR stars can be done in external galaxies at resolutions between 5–10 Å.

The WR stage of stellar evolution gives a unique test of evolutionary theories, and the relative number of WC to WN stars has been used extensively in the Local Group (Maeder & Conti 1994) to put restrictions on the models. Because of their strong spectral characteristics, detecting (and classifying) the WR stars is indeed far more reliable than attempting to photometrically classify the unevolved massive star population (O-type main sequence stars), given their degeneracy in colors. The "Conti scenario" for very massive star evolution (Maeder & Conti 1994) implies that the WC to WN ratio is a strong function of metallicity. This prediction is broadly consistent with the WC/WN ratios observed in the Local Group as a function of metallicity—WC/WN increases with Z. However one exception is the dwarf galaxy IC 10, which is the nearest galaxy-wide starburst. It has a peculiar mix of WR stars; in particular WC/WN = 2, which is a factor 20 times higher than the SMC which is of similar metallicity. In addition, the high numbers of total WR stars imply that IC 10 has the highest relative star formation rate among all the galaxies of the Local Group. This very large WC/WN ratio is still a puzzle and something which requires further study with large telescopes.

Science with the GTC 10-m Telescope (Granada, España, 5-8 febrero 2002)
Editors: José Miguel Rodríguez Espinosa, Francisco Garzón López & Verónica Melo Marín

Initially, it was discovered by Massey & Armandroff (1995), through a narrow band filter technique and studied in more detail by Royer et al. (2001). The latter used a specialized set of five filters placed on the WC- and WN-sensitive features and can classify the stars through the relative magnitudes in each filter. They have recently extended this work to 8 m telescopes (VLT + FORS), using these dedicated filters on the galaxy NGC 300. IC 10 would be an excellent candidate in the north to study in more detail with OSIRIS using these filters. The previous imaging was all done with 4 m telescopes, and, given the high foreground reddening, some of the weak-lined WN stars may have been missed. In addition one would like spectroscopy of the candidates to confirm spectral types and allow detailed model atmosphere analysis. In summary, OSIRIS could be used to disentangle the outstanding star formation and evolution puzzles in this galaxy in particular and extend the work to galaxies beyond the Local Group (e.g., M82 and very extreme metallicity environments).

5. THE WIND MOMENTUM –LUMINOSITY RELATION

As mentioned above, accurate mass loss rates are essential input parameters for evolutionary models, and can be determined empirically from optical spectra of massive stars in other galaxies. An additional use of stellar wind physics is the promising potential to use them as accurate distance indicators to galaxies at up to 10 Mpc by employing the so-called " wind momentum–luminosity relation" (WLR) method. In massive stars, stellar winds are driven by line absorption and the corresponding photon momentum transfer. The "modified wind momenta" of O–B–A-type supergiants depends very strongly on luminosity. The latter can be measured from purely spectroscopic diagnostics of the optical spectra of mid–late B- and A-type supergiants. With an intrinsic luminosity and accurate stellar photometry, a distance follows. Kudritzki et al. (1999) have begun testing and calibrating this method in the Galaxy, and their work suggests that distance determinations to within ±10% are possible. The next step is to determine if the method can be consistently applied in the lower metallicity regions of the Magellanic Clouds, and across the stellar abundance gradients of M31 and M33. Initial work using 4 m class telescopes on stars in these latter two galaxies has shown the promise of the method. For example, Smartt et al. (2001) have presented the quantitative analysis of an early B-type supergiant in M31, showing that it fits nicely in the WLR diagram (an example of which is shown in Figure 2). This is confirmation that the procedure works well beyond distances of the Magellanic Clouds. In that paper, a 4 m telescope (the William Herschel Telescope) was used to gather moderate signal-to-noise and moderate resolution data (∼1 Å for the B-type supergiant) and this was certainly sufficient to support the detailed model atmosphere analysis. However, with GTC and OSIRIS, working at slightly lower resolution (∼2 Å), one will be able to observe such blue supergiants to distances of approximately 10 Mpc from the Milky Way. First applications of the method for galaxies outside the Local Group at 3 and 7 Mpc distance have been published very recently by Bresolin et al. (2001, 2002). The results of this experiment are illustrated in Figure 2, showing the spectra of the most distant single star ever analyzed in such a detailed manner. Bresolin et al. (2001) used VLT + FORS to observe the brightest blue stars in the galaxy NGC 3621 (at a distance of 6.7 Mpc) in multiobject mode. This article is an illustration of the potential of 8 m telescopes and MOS spectrometers in this area, and a full analysis is pending. By applying the WLR. it is hoped that a distance to this galaxy could be determined to within 10%, a result that would come close to competing with Cepheid determination. Using unified model atmosphere analyses has two advantages over the Cepheid method. The first is that a model flux is calculated tjat can be compared with either stellar photometry or the slope of the flux-calibrated stellar continuum to determine reddening towards each star. Determining reddening towards Cepheids has been difficult. Secondly, although the WLR is dependent on metallicity (Kudritzki & Puls 2000), one can determine the overall metallicity of the target stars from the same spectra. The Bresolin et al. (2001) study shows that reasonable estimates of stellar metallicity can be determined by synthesizing the entire observed spectrum. In the case of the star in Figure 2 the metallicity determined is similar to that of the LMC. Hence using high quality spectra from 8–10 m telescopes may allow these luminous objects to be used as distance indicators to check the Cepheid results within 10 Mpc.

I thank the organizers for inviting me to speak and PPARC for financial support in the form of an Advanced Fellowship award. I thank many friends and coworkers for the past several years of discussions and collaborations—Artemio Herrero, Danny Lennon, Paco Najarro, Rolf Kudritzki, Kim Venn, Philip Dufton, Robert Rolleston, Fabio Bresolin, Carrie Trundle, and Pierre Royer.

REFERENCES

Bresolin, F., et al. 2001, ApJ, 548, L159
Bresolin, F., et al. 2002, ApJ, 577, L107
Crowther, P., et al. 2002, A&A, 392, 653
Eggenbeger, et al. 2002, A&A, 386, 576
Kudritzki, R.P., et al. 1999, A&A, 350, 970
Kudritzki, R. P., & Puls, J. 2000, ARA&A, 38, 613
Maeder, A., & Conti, P. 1994, ARA&A, 32, 227
Massey, P., & Armandroff, T. 1995, AJ, 109, 2470
Massey, P., et al. 1995a, AJ, 110, 2715
Massey, P., et al. 1995b, ApJ, 454, 151
Massey, P. 1998, in Stellar Astrophysics for the Local Group, ed. A. Aparicio, A. Herrero, & F. Sanchez (Cambridge: Cambridge Univ. Press), 95
Royer, P., et al. 2001, A&A, 366, L1
Skillman, E., Kennicutt, R. C., & Hodge, P. W. 1989, ApJ, 347, 875
Smartt, S. J., et al. 2001, MNRAS, 325, 257
Venn, K. A., et al. 2001, ApJ, 547, 765

Stephen J. Smartt: Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK (sjs@ast,cam.ac.uk)