Red Supergiant Stars in the Local Group and Beyond

Lee R. Patrick

Doctor of Philosophy
The University of Edinburgh
March 2016

Summary

Red Supergiant (RSG) stars are the brightest stars at infrared wavelengths. Their intrinsic brightness combined with the fact that dust does not obscure observations at these wavelengths, makes these objects very attractive to study in the infrared. To make best use of the future facilities, the tools to study RSGs must be developed today. The aim of this thesis is to further the understanding of RSGs by focusing on measuring their chemical properties in different galaxies.

To do this, I develop an analysis technique that uses observations of RSGs to estimate their properties. Using this analysis technique, I measure the chemistry and dispersal of a young cluster of stars in the Large Magellanic Cloud, one of the closest galaxies to the Milky Way. I find the chemical properties to be in good agreement for the chemical properties of RGSs with previous studies. I also measure the mass the mass of the cluster, for the first time, using the dispersal of the cluster, and show that the mass is consistent with that found using other methods.

I then measure the chemical properties of 11 RSGs in a dwarf irregular galaxy with a turbulent history (NGC 6822), which is 10 times further away than the Large Magellanic Cloud. I find the chemical properties to be in good agreement with other young stars in this galaxy and I present weak evidence for variations in the distribution of the chemical elements in this galaxy, which requires further study.

I then present observations of 22 RSGs in a large galaxy, four times more distant than NGC 6822, which is located outside of our Local Group of galaxies. I am able to rule out that the target RSGs are in binary systems and I estimate the properties of the targets using the analysis routine presented, where I find good agreement with previous studies of young stars in this galaxy.

I conclude this thesis by summarising the main results and present a first-look calibration of the relationship between two fundamental determinants of galaxy evolution: mass and chemical abundance. In addition, using ∼80 RSGs, with surface temperatures estimated in a consistent way, I show that the temperature of RSGs does not appear to depend upon their chemical properties, in disagreement with current models.

Abstract

Red Supergiant (RSG) stars are the most luminous stars in the infrared sky. Their intrinsic luminosities combined with the low dust extinction observed in this regime makes these objects very attractive to study in the near-infrared (IR). In addition, RSGs are necessarily young objects, as, they are tracers of recent star formation in extra-galactic systems. As the next generation of telescopes will be optimised for study in the near-IR, it is clear that, in the coming years, RSGs will play a prominent role in the way that astronomers probe the local Universe and out to larger distances with space-based observations. Therefore, it is vital to better our understanding of these objects now and develop the tools that will allow us to take full advantage of the suite of instrumentation that will become available in the near future. This thesis aims to further the understanding of RSGs by focusing on quantitative studies of near-IR spectroscopic observations.

To this end, I develop an analysis technique that uses spectroscopic and photometric observations to estimate stellar parameters of RSGs. The observations are compared with synthetic spectra extracted from stellar model atmospheres, where departures from local thermodynamic equilibrium have been calculated for the diagnostic spectral lines. This technique is tested thoroughly on synthetic and real observations and is shown to reliably estimate stellar parameters in both regimes when compared with input parameters and previous studies respectively.

Using the analysis routines developed in Chapter **??**, in Chapter **??** I measure the chemistry and kinematics of NGC 2100, a young massive cluster (YMC) of stars in the Large Magellanic Cloud, using near-IR spectroscopic observations of 14 RSGs taken with the new K-band multi-object spectrograph (KMOS). I estimate the average metallicity to be -0.43 ± 0.10 dex, which is in good agreement with previous studies. I compare the observed location of the target RSGs on the Hertzsprung–Russell diagram with that of a Solar-like metallicity YMC and show that there appears to be no significant difference in the appearance of the RSGs in these two clusters. By combining the individual RSG spectra, I create an integrated-light cluster spectrum and show that the stellar parameters estimated, using the same technique as for individual RSGs, are in good agreement with the average properties of the cluster. In addition, I measure – for the first time – an upper limit of the dynamical mass of NGC 2100 to be $15.2 \times 10^4\,\mathrm{M}_\odot$, which is consistent with the literature measurement of the photometric mass of the cluster.

In Chapter **??**, I present observations of RSGs in NGC 6822, a dwarf irregular with a turbulent history, observed with KMOS. The data reduction process with KMOS is described in detail, in particular where the reduction has been optimised for the data. Stellar parameters are estimated using the technique presented in Chapter **??** and an average metallicity in NGC 6822 of -0.55 ± 0.13 dex is found, consistent with previous measurements of young stars in this galaxy. The spatial distribution of metallicity is estimated and weak evidence is found for a radial metallicity gradient, which will require follow-up observations. In addition, I show that the metallicities of the young and old populations of NGC 6822 are well explained using a simple closed-box chemical evolution model, an interesting result, as NGC 6822 is expected to have undergone significant recent interactions.

In Chapter **??**, I present multi-epoch KMOS observations of 22 RSGs in the Sculptor Group galaxy NGC 55. Radial velocities are measured for the sample and are shown to be in good agreement with previous studies. Using the multi-epoch data, I find no evidence for radial velocity variables within the sample. Stellar parameters are estimated for 10 targets and are shown to be in good agreement with previous estimates.

I conclude this thesis by summarising the main results and present a first-look calibration of the relationship between galaxy mass and metallicity using RSGs. By comparing the RSG metallicity estimates to metallicities estimated from $\sim$50 000 Sloan digital sky survey galaxies, I show that the absolute metallicities of the two samples disagree. A more quantitative analysis requires additional RSG observations.

In addition, using $\sim$80 RSGs, with stellar parameters estimated in a consistent way, I show that there appears to be no dependence of the temperature of RSGs upon metallicity. This is in disagreement with current evolutionary models, which display a temperature change of $\sim$450 K over the studied range in metallicity.

Finally, I outline potential areas for future work, focusing on follow-up studies that have been identified as a result of the work done in this thesis.

Declaration

I declare that this thesis was composed by myself, that the work contained herein is my own except where explicitly stated otherwise in the text, and that this work has not been submitted for any other degree or professional qualification except as specified.

Parts of this work have been published in Patrick et al. (2015, 2016).

(*Lee R. Patrick, March 2016*)

Acknowledgements

To acknowledge the contribution of everyone who has helped me complete this thesis in the last three and a half years would, no doubt, contribute significantly to the page count of this thesis. To keep this reasonably concise, I would like to first acknowledge all of the help I've received from the people who do not have a specific mention in this section. All of the friends and work colleagues who have encouraged and spurred me on over the last few years: your contribution is not forgotten and is certainly appreciated.

I would like to thank my supervisor, Chris Evans, for providing excellent support from the outset and keeping me focused on the important tasks in hand, as well as his meticulous quality control, which have improved this thesis greatly. Throughout the course of this thesis, I have had some fantastic opportunities to go observing and attend productive conferences, which is all thanks to Chris' drive and enthusiasm. Chris has been a great supervisor and friend, always using his skills and knowledge to keep me optimistic and striving for the next result.

I would also like to thank all of my collaborators, in particular Ben Davies and Rolf-Peter Kudritzki, for their help and hard work, particularly at some strange times of the day (night, depending upon your time-zone). In addition, I would like to thank my fellow students who have provided support on a huge range of different topics, which has saved me countless time and effort.

On a personal level, I would like to thank Melanie Woodward, who has not only, made this journey of a PhD with me, but also made it so much more enjoyable. Mel has helped me celebrate the highs and helped me get back on the horse during the lows. However, Mel has not only contributed to this thesis on a personal level. The quality of writing in this thesis (I'm not ashamed to say) is high. I'm not ashamed to say that because it is down to the fact that Mel is an excellent editor and has spent hours studying and commenting on this thesis, improving the style, readability and flow greatly.

I would like to thank my fellow students for supporting me on a personal level. The "Golden Age" of U4, which I was lucky enough to be a part of, along with Fergus Cullen and Sandy Rogers, will live long in my memory.

Contents

List of Figures

List of Tables

Appendix A

Acronyms

2MASS Two Micron All Sky Survey
BSG Blue supergiant
CCD Colour–colour diagram (not to be confused with CCD: Charged coupled device; not an accroyn used in this thesis)
CCSN Core-collapse supernova
c.g.s Centimetre-gram-second measurement system
CMD Colour–magnitude diagram
CNO Carbon–nitrogen–oxygen
DKF Davies, Kudritzki & Figer (2010)
DSS Digital sky survey
ESO European southern observatory
FoV Field of view
G14 Gazak (2014)
GRB Gamma-ray burst
GTO Guaranteed time observations
H-R Hertzsprung–Russell
IFS Integral field spectroscopy
IFU Integral field unit
IR Infrared
ISM Interstellar medium
KMOS *K*-band multi-object spectrograph (see Chapter **??**)
LBV Luminous blue variable
LMC Large Magellanic cloud
LTE Local thermodynamic equilibrium (see Chapter **??**)

MOSFIRE Multi-object spectrometer for infra-red exploration
MS Main sequence
MZR Mass-metallicity relationship
NGC New general catalogue
NS Neutron star
OB Observing block
OSIRIS Optical system for imaging and low-intermediate-resolution integrated spectroscopy
PISN Pair instability supernova
PSF Point spread function
RSG Red supergiant
RSGC Red supergiant cluster
SC Schönberg–Chandrasekhar
SDSS Sloan digital sky survey
SMC Small Magellanic cloud
SN Supernova
SV Science verification
VLT Very large telescope
WLT Wolf-Lundmark-Melotte
WR Wolf-Rayet
YMC Young massive cluster

Bibliography

Davies B., Kudritzki R.-P., Figer D. F., 2010, MNRAS, 407, 1203

Gazak J. K., 2014, PhD thesis, University of Hawaii

Patrick L. R., Evans C. J., Davies B., Kudritzki R., Hénault-Brunet V., Bastian N., Lapenna E., Bergemann M., 2016, ArXiv e-prints

Patrick L. R., Evans C. J., Davies B., Kudritzki R.-P., Gazak J. Z., Bergemann M., Plez B., Ferguson A. M. N., 2015, ApJ, 803, 14