IOP Conf. Series: Journal of Physics: Conf. Series **869** (2017) 012062 doi:10.1088/1742-6596/869/1/012062

Monitoring pulsating giant stars in M33: star formation history and chemical enrichment

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Abstract. We have conducted a near-infrared monitoring campaign at the UK InfraRed Telescope (UKIRT), of the Local Group spiral galaxy M33 (Triangulum). A new method has been developed by us to use pulsating giant stars to reconstruct the star formation history of galaxies over cosmological time as well as using them to map the dust production across their host galaxies. In first Instance the central square kiloparsec of M33 was monitored and long period variable stars (LPVs) were identified. We give evidence of two epochs of a star formation rate enhanced by a factor of a few. These stars are also important dust factories, we measure their dust production rates from a combination of our data with *Spitzer* Space Telescope mid-IR photometry. Then the monitoring survey was expanded to cover a much larger part of M33 including spiral arms. Here we present our methodology and describe results for the central square kiloparsec of M33 [1–4] and disc of M33 [5–8].

1. Introduction

Luminous, cool evolved stars are powerful tracers of the underlying stellar populations, as they stand out above all other stars especially at infrared wavelengths and are thus the first stars that can be resolved in increasingly distant galaxies. Asymptotic Giant Branch (AGB) stars in particular represent stellar populations ranging in age from tens of millions of years (i.e. "the present") to more than ten billion years (formed at redshift ~ 2). The cool molecular atmospheres of AGB stars lead to broad absorption troughs in their optical spectra; while normally these are oxygen-bearing molecules such as TiO and VO, stars in certain mass ranges dredge up carbon – that had been synthesized in their interiors – and replace the absorption bands by entirely different ones due to C_2 and CN. This changes their colours, generally rendering carbon stars redder than their oxygen (M-type) counterparts. In principle, this makes them easy to distinguish photometrically.

Triangulum offers a superb opportunity to study the structure and formation history of a spiral galaxy, and to study various aspects of stellar evolution. The galaxy is sufficiently massive to contain large populations of stars to be used as tracers of star formation, and to sample brief phases of stellar evolution such as those associated with strong mass loss on the AGB. Its disc is seen under a more favourable viewing angle than the larger Andromeda galaxy (M31), and also its more modest size ($\sim 1^\circ$) makes it easier to study it in its entirety. The methodology comprises three stages: firstly, we find stars that vary in brightness with large amplitude (typically a magnitude) and long period (months to years), and identify them on


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the basis of their colours and luminosity as cool giant stars at the endpoints of their evolution. Secondly, we use the fact that these stars no longer evolve in brightness, to uniquely relate their brightness to their birth mass, and use the birth mass distribution to reconstruct the star formation history (SFH). Lastly, we measure the excess infrared emission from dust produced by these stars, to quantify the amount of matter they return to the interstellar medium in M33.

2. Observations

The project exploits a large observational campaign between 2003-2007, an investment of over 100 hr on the UK InfraRed Telescope (UKIRT). In first instance, only the central square kiloparsec ("bulge") were monitored and analysed, with the UIST camera. Previously, we presented the variable star catalogue and SFH [1, 2], where we found a main formation epoch of redshift 1 but with fluctuations up to the present day. As the new wide-field camera (WFCAM) became available, the campaign was expanded to cover two orders of magnitude larger area, comprising the disc of M33 and its spiral arms. Also, we presented the photometric catalogue of WFCAM data [5, 6]. This catalogue comprises of 403 734 stars, among which 4643 stars were identified as LPVs– AGB stars, super–AGB stars and RSGs [9].

3. Star formation history

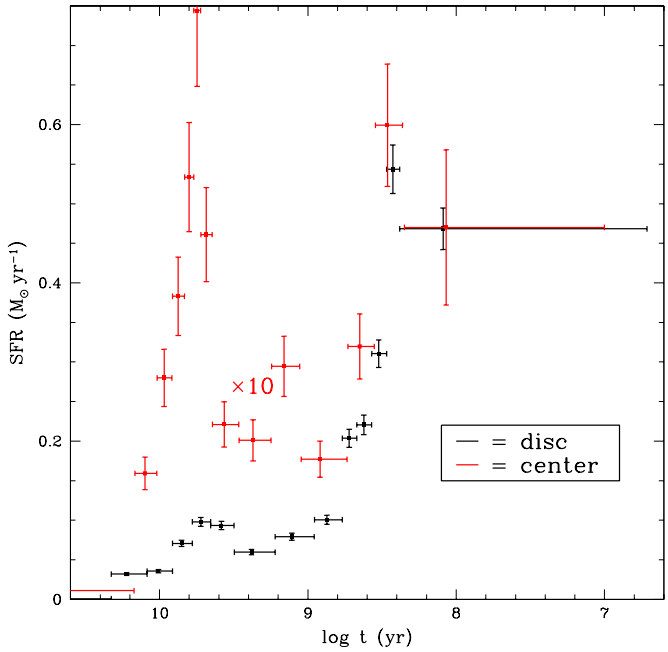


Figure 1. The SFH of M33 in the disc (black) and in the center (red).

Resolved stellar populations within galaxies allow us to derive star formation histories on the basis of colour magnitude diagram modelling, rather than from integrated light. The LPVs are at the end-points of their evolution, and their luminosities directly reflect their birth mass (via the core mass). Stellar evolution models provide this relation. The distribution of LPVs over luminosity can thus be translated into the star formation history, assuming a standard initial mass function. LPVs were formed as recently as < 10 Myr ago and as long ago as > 10 Gyr, so they probe almost all of cosmic star formation. We have successfully used this new technique in

M 33 [2,8], the Magellanic Clouds [10] and NGC 147 and NGC 185 [11,12], using Padova models which also provide the lifetimes of the LPV phase.

In figure 1, we present the SFH for the center and disc of M 33. In the central regions two main epochs of star formation are seen; one that occurred $\sim$ 4–5 Gyr ago, peaking around 4 Gyr ago at a level$\sim$ 2.5 times as high as during the subsequent couple of Gyr and the one that occurred $\sim$ 300 Myr–20 Myr ago with a rate $\sim$ 1.5 times higher than the aforementioned peak. Two main epochs of star formation are also seen in the disc of M 33; one that occurred $\sim$ 6 Gyr ago and lasted $\sim$ 3 Gyr and the one that occurred $\sim$ 250 Myr ago and lasted $\sim$ 200 Myr. More that 71 % of stars mass in M 33 were created during the first epoch of star formation and less than 13 % were created during the recent epoch of star formation.

4. Dust production rate of evolved stars

A majority of LPVs have been detected at mid-IR wavelengths with *spitzer* Space Telescope [13]. Therefore, we can estimate the dust production rates across a galactic disc of M 33. We derive mass-loss rates and luminosities in two steps. First, we use DUSTY code [14] to model the spectral energy distributions (SEDs) of LPVs for which mid-IR counterparts have been identified to construct relations between the dust optical depth and bolometric corrections on the one hand, and near-IR colours on the other. Then, by using these relations, we convert the near-IR colours of all red giant variables to luminosities and mass-loss rates.

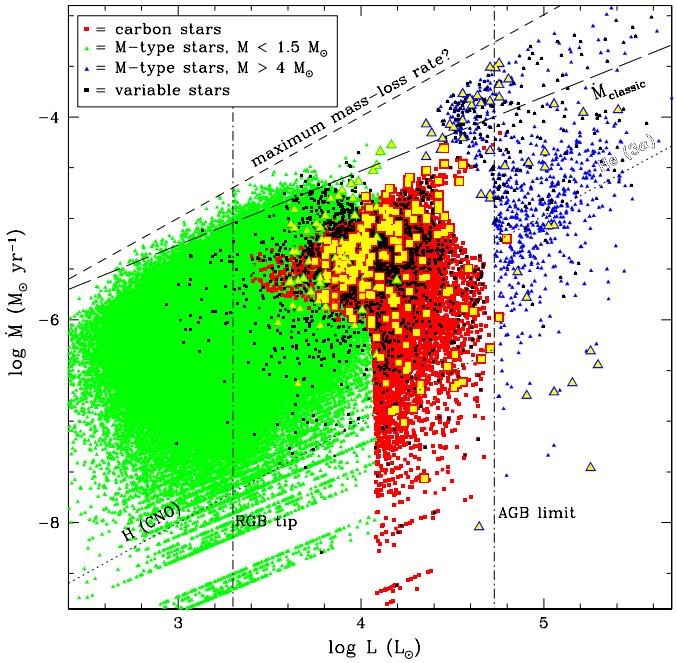


Figure 2. Mass-loss versus luminosity for all stars including non-variable stars. The blue and green triangles show the massive luminous M-type stars and low-mass stars (at lower luminosities), respectively. The red squares show the AGB carbon stars. Large yellow symbols identify the stars modelled with DUSTY [14]; other UKIRT variables are identified by black squares. The vertical dash–dotted lines show the tip luminosity of the RGB and classical limit of the most massive AGB stars (Hot Bottom Burning effects are excluded). The dotted lines show the mass-consumption rates by shell hydrogen burning (CNO cycle) on the AGB and core helium burning (triple-α reaction) in red supergiants. The dashed lines show the limits to the mass-loss rate in dust-driven winds due to single scattering (classic) and multiple scattering.

5. Ongoing-work and conclusions

Currently, we are using the mass-loss rates to investigate the correlations between the dust production rate, luminosity, and amplitude. Also, we are trying to establish a link between the dust return and the formation of stars within the prominent spiral arm pattern. We will show where mass is returned, how this compares to the gas in spiral arms and inter-arm regions, and from this we will estimate gas recycle times and gas depletion in star formation.

In conclusion, using a new technique developed by us, we showed how the SFH varies across M33, e.g. whether star formation has propagated inwards or outwards through the disc. Also, we measured the lag between stars of different ages and the spiral arms in which they were formed.

Acknowledgments

We are grateful for financial support by The Leverhulme Trust under grant No. RF/4/RFG/2007/0297, by the Royal Astronomical Society, and by the Royal Society under grant No. IE130487.

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