**SUSTAINING GALAXY EVOLUTION: THE ROLE OF STELLAR FEEDBACK**

Atefeh Javadi¹, Jacco Th. van Loon², and Habib Khosroshahi¹

¹School of Astronomy, Institute for Research in Fundamental Sciences (IPM), P.O. Box 19395-5531, Tehran, Iran
²Astrophysics Group, Lennard-Jones Laboratories, Keele University, Staffordshire ST5 5BG, UK

E-mail: atefeh@ipm.ir

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**ABSTRACT**

We have conducted a near-infrared monitoring campaign at the UK InfraRed Telescope (UKIRT), of the Local Group galaxy M33. The main aim was to identify stars in the very final stage of their evolution, and for which the luminosity is more directly related to the birth mass than the more numerous less-evolved giant stars that continue to increase in luminosity. The pulsating giant stars (AGB and red supergiants) are identified and their distributions are used to derive the star formation rate as a function of age. 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. The mass-loss rates are seen to increase with increasing strength of pulsation and with increasing bolometric luminosity. Low-mass stars lose most of their mass through stellar winds, but even super-AGB stars and red supergiants lose ∼40% of their mass via a dusty stellar wind. We construct a 2-D map of the mass-return rate, showing a radial decline but also local enhancements due to agglomerations of massive stars. By comparing the current star formation rate with total mass input to the ISM, we conclude that the star formation in the central regions of M33 can only be sustained if gas is accreted from further out in the disc or from circum-galactic regions.

**Key words:** Galaxy: M 33: evolution

1. **INTRODUCTION**

M 33 is the nearest spiral galaxy besides the Andromeda galaxy, and is seen at a more favorable angle. This makes M 33 ideal to study the structure and evolution of a spiral galaxy. We will therefore learn how our own galaxy, the Milky Way, formed and evolved, which is difficult to do directly due to our position within its dusty disc. Asymptotic Giant Branch (AGB) stars trace stellar populations from as young as ∼30 Myr to as old as the oldest globular clusters. Because they are luminous (∼10⁴L⊙) and cool (T_{eff} ≤ 4000K), they dominate the light of the galaxy at near–IR wavelengths, where extinction is relatively small, at high contrast with the underlying main–sequence populations. This makes AGB stars powerful probes of a galaxy’s star formation history.

AGB stars undergo radial pulsations. The period (P ∼ 10^{-3}d) depends on the total mass of the star, while the luminosity depends on the core mass, with both the period and luminosity increasing as the mass increases. On the AGB, more than half of the mass is lost to the interstellar medium (ISM) in the form of a dusty wind (van Loon et al., 2005). Mass loss is of great importance for stellar evolution, as the end products including supernovae, but also for the chemical enrichment of a galaxy. AGB stars are the principal contributioners of molecules and dust, and a major source of carbon and nitrogen.

The methodology comprises three stages: [1] find stars that vary in brightness with large amplitude (about a magnitude) and long period (months to years), and identify them by their colours and luminosity as cool giant stars at the endpoints of their evolution; [2] 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 construct the star formation history (SFH); [3] measure the excess infrared emission from dust produced by these stars, to quantify the amount of matter they return to the interstellar medium in M 33.

2. **OBSERVATIONS**

Observations were done with three of UKIRT’s imagers: UIS, UFTI and WFCAM. UIS and UFTI cover the central part (∼1 kpc) and WFCAM covers a much larger part of M 33 (13 kpc×13 kpc). The combined, square–degree mosaic of M 33 in the K–band is shown in Fig. 1. The square–kpc central area is represented with a box.

The survey and identification of variable stars are described in detail in Javadi et al. (2011, paper I) and
Javadi et al. (2014, paper IV); 812 variable stars were identified in the central square kiloparsec of M 33 using multi–epoch UIST data and 4643 variable stars were found across the galactic disc of M 33 using multi–epoch data from WFCAM.

2.1. Spatial Distribution of LPVs

Maps of the surface density of the number of Long Period Variable stars (LPVs), AGB stars, RGB stars and massive stars are shown in Fig. 2. The variable star, AGB star and massive star distributions showing central concentrations, but the RGB stars do not show such a strong central concentration. Only hints of the spiral arms is seen in these maps.

3. THE STAR FORMATION HISTORY IN M 33

In Javadi et al. (2011, paper II), we have developed a novel way to derive the star formation history of galaxies by using large–amplitude variable stars which are identified in our IR monitoring program. We used the fact that these variables have reached the very final stages of their evolution, and their brightness can thus be transformed into their mass at birth by employing theoretical evolutionary tracks, or by isochrones. Therefore, we could simply construct a link between observed K–band magnitude and theoretical models to estimate the birth mass of LPVs. This is done in paper II for four different metallicities from super–solar metallicities to sub–solar metallicities. As described in paper II, the central region of M 33 has approximately solar metallicity so we adopt Z=0.015. The star formation history is estimated by:

\[ \xi(t) = \frac{dn'(t)}{dt} \int_{\min(m(t)+dt)}^{\max(m(t))} f_{IMF}(m)mdm, \]

Where \( n' \) is the number of variables that we have identified, \( f_{IMF} \) is the initial mass function describing the relative contribution to star formation by stars of different mass and \( \delta t \) is the duration of variability for which these stars display strong radial pulsation.

The SFH in the central square kpc of M 33 is shown in Fig. 2. Two main epochs of star formation are obvious; a major epoch of formation \( \approx 4–8 \) Gyr ago (log \( t=9.6–9.9 \) reaching around 6 Gyr ago (log \( t=9.8 \)) at a level about three times as high as during the subsequent couple of Gyr. A second epoch of star formation is seen to have occurred from \( \sim 200–300 \) Myr ago (log \( t=8.3–8.5 \)), reaching nearly the same level as the 6 Gyr peak (log \( t=9.8 \)). Since then the rate of star formation has decreased.

4. MASS LOSS RATES IN THE CENTRAL SQUARE KILOPARSEC OF M 33

To derive the mass–loss rates of the red giant variables, first we model the spectral energy distribution of near-IR variables for which we have Spitzer data (Fig. 3) and then we use these results to construct relations between the dust optical depth and bolometric corrections on the one hand, and near-IR colours on the other. Then we apply these relations to other red giants stars with no Spitzer detection to derive the mass–loss rates (Fig. 4).

The total mass return from UKIRT variables is almost \( \approx 0.0055 \; M_\odot \text{yr}^{-1} \) and carbon grains make up \( < 23 \% \) of the present–day dust–mass return so the interstellar dust is predominantly oxygen–rich.

The mass return by low–mass stars and carbon stars is fairly uniform across the central region, but three areas at \( r\sim0.3–0.4 \) kpc from the center have much higher mass–return rates due to contributions of several massive, very dusty stars. This could feed – and chemically enrich – enduring or new star formation in those areas.
on timescales of a couple of $10^7$ yrs.

The estimated ISM depletion timescale by Kang et al. (2012) is 0.3 Gyr. Thus the mass return from evolved stars would not change the timescale by more than 17%. If we take into account the mass return from supernovae, hot massive-star winds, luminous blue variable eruption, et cetera, the mass return rate increases from $\sim 0.004 - 0.005 \ M_\odot yr^{-1} kpc^{-2}$ to $\sim 0.006 \ M_\odot yr^{-1} kpc^{-2}$. Therefore, the above conclusion does not change. To sustain star formation at the current rate gas must flow into the central regions of M 33, either through a viscous disc or via cooling flows from the circum–galactic medium.

5. ON-GOING WORK AND CONCLUSION

Currently we are working on the data from WFCAM which cover the disc of M 33. The global star formation history has been derived and we are estimating the mass loss rates of evolved stars in this region. We will thus show how SFH varies across M33, e.g. whether star formation has propagated inwards or outwards through the disc; we will measure the lag between stars of different ages and the spiral arms in which they formed; and we will show where mass is returned, how this compares to the gas in spiral arms and inter-arm regions, and from this estimate gas recycle times and gas depletion in star formation.

In conclusion, our proposed method to derive the star formation history from LPVs has been validated for the central regions as well as the disc of M33 and it suggests that the super–AGB phase of stellar evolution should be reviewed again.

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REFERENCES

Figure 5. Mass-loss rate vs. luminosity. Massive, luminous M-type stars are depicted by blue triangles; AGB carbon stars by red squares; and low-mass M-type stars (at lower luminosities) by green triangles. Large yellow symbols identify the stars modelled with dusty; other UKIRT variable stars are identified by black squares. The most extreme mass-losing stars are labelled.

Figure 6. Top: Spitzer composite image of IRAC bands 1, 2 and 4 at respectively 3.6 \( \mu \)m (blue), 4.5 \( \mu \)m (green) and 8 \( \mu \)m (red); Bottom: map of mass-return-rate surface density over the central region of M 33.