Why Galaxies Care About AGB Stars:
A Continuing Challenge through Cosmic Time
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AGB population as probes of galaxy structure and evolution

Atefeh Javadi[1] **and Jacco Th. van Loon**[2]

[1]School of Astronomy, Institute for Research in Fundamental Sciences (IPM), P.O. Box 19395-5531, Tehran, Iran
email: atefeh@ipm.ir

[2]Lennard-Jones Laboratories, Keele University, ST5 5BG, UK
email: j.t.van.loon@keele.ac.uk

Abstract. The evolution of galaxies is driven by the birth and death of stars. AGB stars are at the end points of their evolution and therefore their luminosities directly reflect their birth mass; this enables us to reconstruct the star formation history. These cool stars also produce dust grains that play an important role in the temperature regulation of the interstellar medium (ISM), chemistry, and the formation of planets. These stars can be resolved in all of the nearby galaxies. Therefore, the Local Group of galaxies offers us a superb near-field cosmology site. Here we can reconstruct the formation histories, and probe the structure and dynamics, of spiral galaxies, of the many dwarf satellite galaxies surrounding the Milky Way and Andromeda, and of isolated dwarf galaxies. It also offers a variety of environments in which to study the detailed processes of galaxy evolution through studying the mass-loss mechanism and dust production by cool evolved stars. In this paper, I will first review our recent efforts to identify mass-losing Asymptotic Giant Branch (AGB) stars and red supergiants (RSGs) in Local Group galaxies and to correlate spatial distributions of the AGB stars of different mass with galactic structures. Then, I will outline our methodology to reconstruct the star formation histories using variable pulsating AGB stars and RSGs and present the results for rates of mass–loss and dust production by pulsating AGB stars and their analysis in terms of stellar evolution and galaxy evolution.

Keywords. stars: luminosity function, mass function – stars: AGB and post–AGB – stars:mass–loss – galaxies: evolution – galaxies: individual: M 33 – galaxies: spiral – galaxies: dwarf – galaxies: stellar content – galaxies: structure

1. Introduction

Stars can be resolved in all of the Local Group galaxies. This allows the reconstruction of star formation histories (SFHs) by modelling the colour–magnitude diagram, or by using the luminosity distribution of specific stellar tracers. These galaxies have accurate distances based on the tip of the red giant branch (RGB), period–luminosity relation of relatively young Cepheids, or luminosities of old RR Lyrae. Cool evolved stars are among the most accessible probes of stellar populations due to their immense luminosity, from 2000 $L_\odot$ for tip–RGB stars, $\sim 10^4$ $L_\odot$ for asymptotic giant branch (AGB) stars, up to a few 10^5 $L_\odot$ for red supergiants. Their spectral energy distributions (SEDs) peak around 1 μm, so they stand out in the I–band (and reddening is reduced at long wavelengths). They have low surface gravity causing them to pulsate radially on timescales of months to years (Yuan *et al.* 2018). The most extreme examples among these long–period variables (LPVs) are Mira (AGB) variables, which can reach amplitudes of ten magnitudes at visual wavelengths. LPVs vary on timescales (not always strictly periodic) from $\sim$ 100 days for low mass AGB stars ($\sim$ 1 $M_\odot$; 10 Gyr old) to $\sim$ 1300 days for the dustiest massive AGB stars ($\sim$ 4–8 M$_\odot$; 30–200 Myr old); $\sim$ 600–900 days for red supergiants ($\sim$ 8–30 M$_\odot$; 10–30 Myr old). The variability helps identify these beacons; their luminosities can be used to reconstruct the star formation history; and their amplitudes pertain to the process by which they lose matter and ultimately terminate their evolution (van Loon *et al.* 2008; McDonald & Zijlstra 2016). The diagnostic power of LPVs has been demonstrated in M 33 (Javadi *et al.* 2013, 2017) and was illustrated once again by the discovery of a massive (5 M$_\odot$) LPV in the Sagittarius dwarf irregular galaxy (Whitelock *et al.* 2018).

In this project we aim: to construct the mass function of LPVs and derive from this the star formation history in different galaxy types; to correlate spatial distributions of the LPVs of different mass with galactic structures (spheroid, disc and spiral arm components); to measure the rate at which dust is produced and fed into the ISM; to establish correlations between the dust production rate, luminosity, and amplitude of LPVs; and to compare the *in situ* dust replenishment with the amount of pre–existing dust.

2. LPVs in nearby galaxies

Nearby galaxies in the Local Group provide excellent opportunities for studying dust–producing late stages of stellar evolution over a wide range of metallicity. This enables to study the detailed processes of galaxy evolution. Furthermore, we can investigate the formation histories, and probe the structure and dynamics, of spiral galaxies, of the many dwarf satellite galaxies surrounding the Milky Way and Andromeda, and of isolated dwarf galaxies.

2.1. *LPVs in M 33 galaxy*

The only spiral galaxies in the Local Group besides the Milky Way are M 31 and M 33. M 31 is highly inclines ($i \sim 77^\circ$), and extinction therefore remains a problem. With inclination of $i = 56^\circ$, and at d = 950 kpc only slightly more distant, M 33 is positioned much more favourably. Also, in contrast to M 31 the prominent disk of Sc galaxy M 33 bears evidence of recent star formation.

WFCAM and UIST on the UK InfraRed Telescope (UKIRT) was used to identify mass–losing AGB stars and red supergiants in M 33 galaxy from the central square kpc region to a square degree area (Fig. 1). K–band observations were complemented with occasional observations in J– and H–band to provide colour information. The photometric catalogue of the disc comprises 403 734 stars, among which 4643 stars display large–amplitude variability (Javadi *et al.* 2015). Likewise for the bulge we identified 18 398 stars among which 812 were identified as exhibiting large–amplitude variability (Javadi *et al.* 2010).

2.2. *LPVs in dwarf galaxies*

Among the pertinent questions regarding the dwarf galaxies are to what extent–and when–their star formation was quenched by gas removal mechanisms, be it as a result of internal feedback (e.g., supernova explosions) or external processes such as the interaction with massive haloes (Weisz *et al.* 2015). Can dwarf galaxies be rejuvenated, as some seem to harbour relatively young stars? Is gas only removed from dwarf galaxies by tidal or ram-pressure stripping, or can it also be (re–)accreted? To what extent is stellar death able to replenish (metals, dust) the interstellar medium, and to what extent does it heat it and drive galactic winds? Their star formation histories are among the clearest tracers of these processes having–or not having–occurred. Understanding the history of dwarf galaxies may also help us understand stellar streams and minor mergers, and massive globular clusters. A description of stellar mass–loss and dust production is of general

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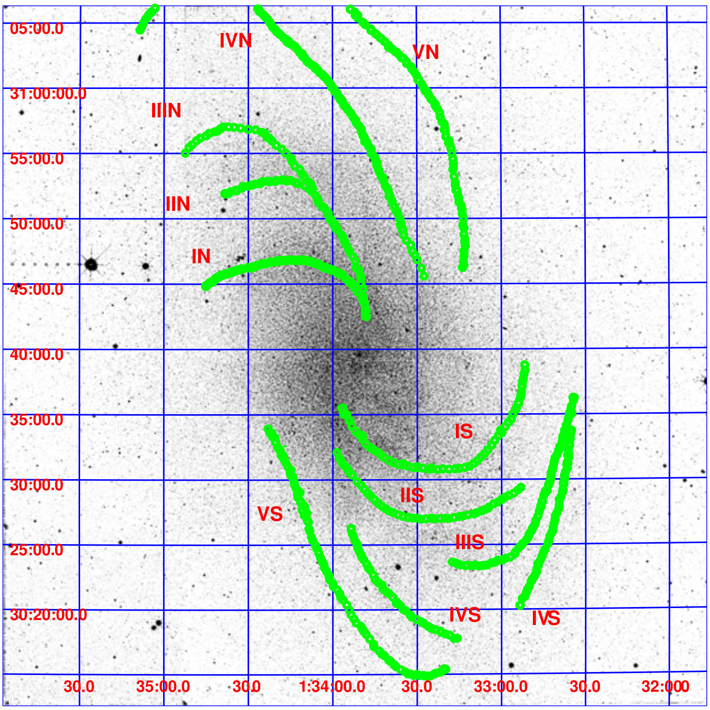

Figure 1. WFCAM K–band mosaic of M 33 with the system of five sets of spiral arms marked on it.

importance for understanding stellar and galaxy evolution. To answer the mentioned questions one the of robust ways is to identify the LPVs as tracers of galaxies star formation histories and chemical enrichment.

The LPVs are identified in some of the galaxies in the Local Group via long term monitoring surveys. In addition, a majority of dwarf galaxies have been observed with *Spitzer* at 3.6 and 4.5 μm via DUSTiNGS project (DUST in Nearby Galaxies with *Spitzer*; Boyer *et al.* 2015a,b). Due to lack of the monitoring survey of dwarf galaxies we started to monitor these galaxies with Isaac Newton Telescope (INT) with the purpose of identifying variable AGB stars (Saremi *et al.* 2017).

2.2.1. INT monitoring survey of dwarf galaxies in the Local Group

While the Milky Way satellite galaxies are spread all over the sky, a Northern hemisphere survey alone can be complete for the Andromeda system of satellite galaxies. Such a survey will benefit from the homogeneity in the distances and hence completeness and accuracy, and foreground populations and extinction are modest and similar between all Andromeda satellites. Surveying an entire satellite system enables us to determine variations among satellites due to their infall histories, cosmic reionization, and internal processes, and to examine how these variations depend on their structural properties such as total mass, gas mass, and distance to their galaxy host. For instance, the NGC 147 and NGC 185 pair are equal in mass but they differ in star formation history and gas content Weisz *et al.* 2015). We can also consider the system of satellites as a whole, and add sparse populations of stellar tracers within individual dwarf galaxies to mimic a much larger galaxy that has sufficient statistical value. About 20 Andromeda satellites

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are known to date, and their small number is the main limit on how clearly one can find trends and variance among them.

Individual Milky Way satellites observed as a comparison to the Andromeda system –is the Andromeda system a universal template for galaxy evolution, or just one particular case? Likewise, isolated galaxies such as Sextans A and B– or the massive and gas–rich IC 10 serve as references against which to assess the effects of galactic harassment affecting satellites. While a good few dwarf galaxies have been monitored over short campaigns to detect RR Lyrae and in some cases Cepheids, only a few (Southern) galaxies have been monitored (in the infrared) over sufficiently long periods of time (>year) to identify LPVs leaving a vast terrain unexplored. Looking ahead, the most luminous LPVs can be found as far away as the massive spiral galaxy M 101 (7 Mpc) to identify dusty supernova progenitors for spectroscopic follow–up with the James Webb Space Telescope.

We observed in I–band for identification of LPVs, as this is where the contrast between the LPVs and other stars is greatest, the bolometric corrections to determine luminosities are smallest, and the effects of attenuation by dust are minimal. However, we also monitored in the V–band. We prioritised the 62 targets, principally on the basis of their estimated number of AGB stars –populous galaxies include IC 10 ($> 10^4$ AGB stars) and Sextans A and B ($> 10^3$ AGB stars). We monitored the entire Andromeda system of satellites; next highest priority was given to isolated and/or gas–rich galaxies. We included distant globular clusters Pal 3 and 4, and NGC 2419 (Galactocentric distances 90–111 kpc) to investigate their connection to nucleated dwarf galaxies. Ultra–faint Milky Way satellites were given the lowest priority as they will have few (or no) LPVs. The face–on spiral galaxies M 101 and NGC 6946 are included to identify the red supergiant and super–AGB progenitors of imminent supernovae (9 SNe have been noticed over the past century in NGC 6946 (The Fireworks Galaxy). The $34'$ wide field of the INT camera covers each galaxy in one pointing, but dithering between repeat exposures is required to fill the gaps between the detectors. Even among the Andromeda system of satellites, none are near enough to one another to fit within one and the same field of view.

In this monitoring survey we aim to [1] reconstruct the SFHs, [2] perform accurate modelling of their SEDs, and [3] study the relation between pulsation amplitude and mass–loss (in conjunction with infrared measures of the dust, and theoretical models).

3. From LPVs counts to SFH

The LPVs are at the end points of their evolution and therefore their luminosity can be directly translated into their birth mass; this enables us to reconstruct the star formation history. The star formation history is described by the star formation rate, ξ, as a function of look-back time ("age"), t:

$$\xi(t) = \frac{f(K(M(t)))}{\Delta(M(t)) f_{\rm IMF}(M(t))}, \tag{1}$$

where $f(K)$ is the observed K-band distribution of pulsating giant stars, Δ is the duration of the evolutionary phase during which these stars display strong radial pulsation, and $f_{\rm IMF}$ is the Initial Mass Function describing the relative contribution to star formation by stars of different mass. Each of these functions depends on the stellar mass, M, and the mass of a pulsating star at the end of its evolution is directly related to its age (t) (Fig. 2). This new technique was successfully used in M 33 (Javadi *et al.* 2011a,b, 2017) the Magellanic Clouds (Rezaeikh *et al.* 2014), NGC 147 & NGC 185 (Golshan *et al.* 2017) and IC 1613 (Hashemi *et al.* 2018). The main results that we found in these galaxies are summarised as below:

• The disc of M 33 was built > 6 Gyr ago, when most stars in M 33 $\approx 73\%$ were formed. The second enhanced epoch of star formation in M 33 occurred ~ 250 Myr ago and

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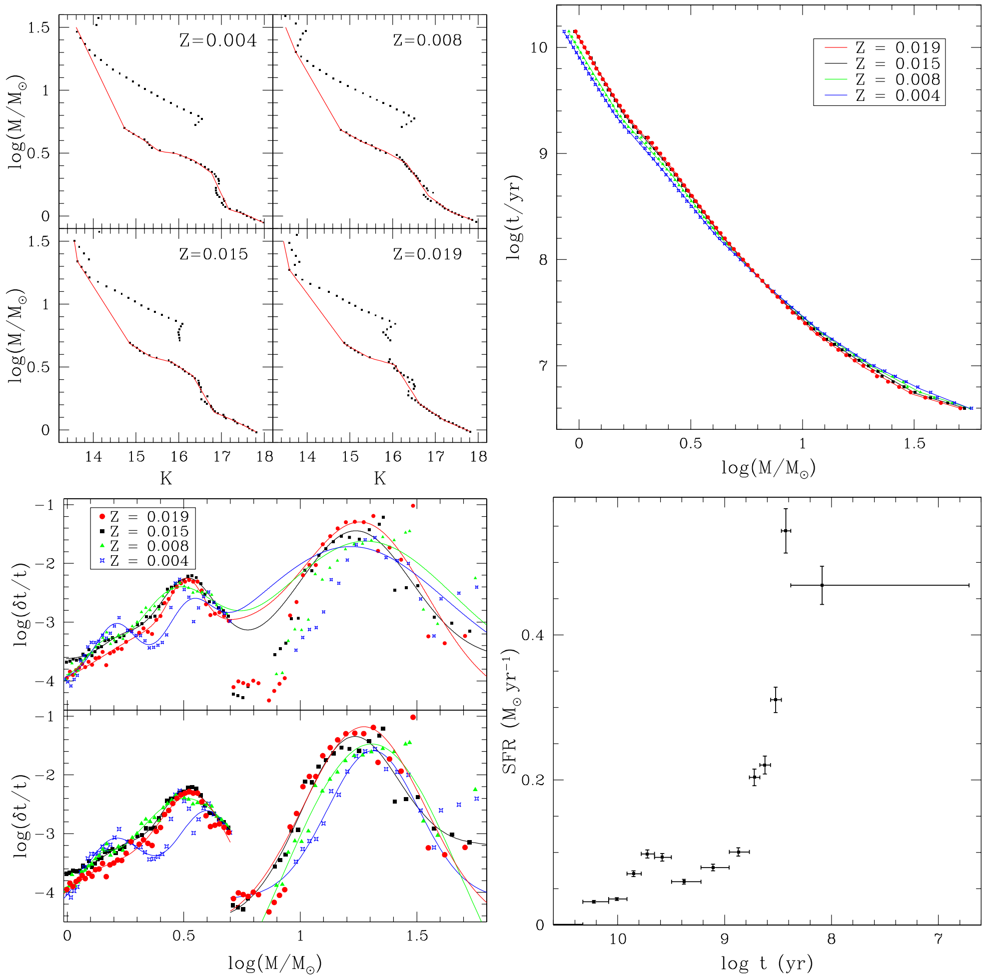

Figure 2. From LPVs counts to SFH (*Top left:*) Mass–Luminosity relation for $Z = 0.019$, 0.015, 0.008 and 0.004. The solid lines are the linear spline fits; (*Top right:*) (Birth) Mass–Age relation for AGB stars and red supergiants derived from the Marigo *et al.* (2008) isochrones; (*Bottom Left:*) Mass–Pulsation relation; (*Bottom right:*) The SFH across the entire disc of M 33.

contributed $\sim 6\%$ to M 33's historic star formation. Radial star formation history profiles suggest that the inner disc of M 33 was formed in an inside–out formation scenario.

• We found a significant difference in the ancient SFH of the LMC and the SMC. For the SMC the bulk of the stars formed a few Gyr later than the LMC. A secondary peak of SFH at ~ 700 Myr ago in the LMC and the SMC is possibly due to the tidal interaction between the Magellanic Clouds and their approach to the Milky Way.

• In spite of similar mass and morphological type, NGC 147 and NGC 185, which are two of the massive satellites of the Andromeda galaxy reveal completely different SFHs. NGC 185 formed earlier than NGC 147 but its star formation continued until recent times with almost constant rate while the star formation in NGC 147 quenched at least 300 Myr ago. These results are corroborated by strong tidal distortions of NGC 147 and the presence of gas in the centre of NGC 185.

• We do not find any enhanced period of star formation over the past 5 Gyr in IC 1613, which suggests that IC 1613 may have evolved in isolation for at least that long.

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4. AGB stars as probes of galaxy structure

Populations of stars formed at different times may also reveal some of the galactic structures in M 33 galaxy. To this aim we separated the stars in our catalogue into massive stars, AGB stars, and RGB stars, on the basis of K-band magnitude and $J--K$ colour criteria. In the central parts, the AGB distribution shows clear signs of a double-component profile, with the break occurring around $r \sim 0.4$ kpc, so in this case we fitted a Sérsic profile, with $R_{\rm e} = 0.30$ kpc and $n = 1.09$ (Javadi *et al.* 2011b). Possibly we are dealing with a bar–like feature, which is a disc-related structure and may be connected to the footpoints of the spiral arms. In addition, the spatial distributions of the massive stars, intermediate-age Asymptotic Giant Branch (AGB) stars and generally old Red Giant Branch (RGB) stars in this region suggest that young and intermediate-age stars were formed within the disc, while the oldest stars may inhabit a more dynamically-relaxed configuration. Interestingly, the massive stars concentrate in an area South of the nucleus, and the intermediate–age population shows signs of a "pseudo–bulge" that however may well be a bar–like feature. Furthermore, the distribution of stars with respect to five spiral arms in M 33, suggests that there is no evidence for a lag associated with the density wave having passed through the position of evolved stars, or any asymmetry at all. This means that spiral arms are transient features and not part of a global density wave potential. Based on these results, we concluded that dynamical mixing operates on timescales <100 Myr (Javadi *et al.* 2017).

5. From mass–loss rates of LPVs to chemical enrichment of the galaxies

The LPVs are also important sources of dust and gas within galaxies. The variability of these cool evolved stars can be used to study their evolutionary state and mass loss. The pulsations are strongest when the mass loss also becomes strongest–it is likely that the pulsations help drive the outflow, assisted by dust formation inside the shocked elevated atmosphere (allowing radiation pressure to drive a wind) and possibly by mechanical or electro–magnetic waves. To estimate the mass–loss rate of variable stars we use the combination of near–IR and mid–IR data. In the case of M 33 almost 2000 variable stars have also been identified by *Spitzer* (Javadi *et al.* 2013, and in preparation). We modelled SEDs of variables stars with at least two measurements in near–IR bands and two mid–IR bands using the publicly available dust radiative transfer code DUSTY (Ivezić & Elitzur 1997). In addition 24–μm sources from Montiel *et al.* (2015) were modelled, because they contribute a large fraction to the total dust and mass return (Table 1, Fig. 3). Our results suggest that the mass–loss rate is approximately proportional to luminosity (and hence birth mass) with almost weaker dependence to pulsation period and/or amplitude (reflecting stellar evolution). In addition, the total mass lost by evolved stars ($\dot{M} \sim 0.1$ $M_\odot$ yr^{-1}) falls short by about a factor of four to sustain stars formation with a current rate, therefore requiring external sources of gas supply (Javadi *et al.* in preparation).

6. On–going works and conclusion

We are currently extending our M 33 study to the dwarf galaxies in the Local Group, to derive star formation history and dust production rate. We aim to identify all LPVs and obtain accurate time–averaged photometry and amplitudes of variability for all red giants and supergiants in the dwarf galaxies at Local Group.

In conclusion, this kind of research which is based on resolved AGB populations, is very important from both theoretical and observational perspectives; Firstly, it will give an unprecedented map of the temperature and radius variations as a function of luminosity and metallicity for mass-losing stars at the end of their evolution, which places important

Table 1. List of 24 μm variables in M 33, with UKIRT ID No. (Javadi *et al.* 2015). The luminosities and mass-loss rates are derived from SED fits, which should be appropriate for AGB stars and RSGs but not YSOs.

name	ID	RA(2000)	DEC (2000)	$\log L/\mathrm{L}_\odot$	$\log \dot{M}$ ($\mathrm{M}_\odot$ yr^{-1})	variable?	type
2	311369	01:34:22.85	+30:34:09.9	5.17	−2.79	no	YSO?
4	39836	01:33:32.64	+30:36:55.5	5.06	−3.37	no	YSO?
6	304069	01:33:29.70	+30:24:08.6	4.61	−3.56	yes	AGB
7	17077	01:34:12.95	+30:29:38.5	4.81	−3.55	no	AGB?
	160486	01:34:12.87	+30:29:40.1			no	AGB?
8	305279	01:33:28.38	+30:36:47.9	4.52	−3.75	yes	AGB
9	304597	01:34:27.85	+30:43:40.0	4.66	−3.65	yes	AGB
10	252686	01:33:50.06	+30:16:31.7	4.41	−3.66	probably	AGB
13	16033	01:33:26.65	+30:57:14.4	4.76	−3.80	yes	AGB?
14	453	01:34:12.25	+30:53:14.1	5.46	−4.60	no	RSG
16	8656	01:33:47.34	+30:16:32.4	4.52	−4.09	yes	AGB
17	24352	01:33:49.86	+30:52:41.3	5.06	−3.55	yes	RSG?
20	249854	01:33:19.68	+30:31:05.1	4.26	−4.04	probably	AGB
21	53418	01:33:41.54	+30:14:12.7	4.44	−4.03	yes	AGB
22	182878	01:33:37.43	+30:55:50.4	3.96	−3.46	no	YSO
23	43590	01:34:09.40	+30:55:18.2	4.41	−4.09	yes	AGB

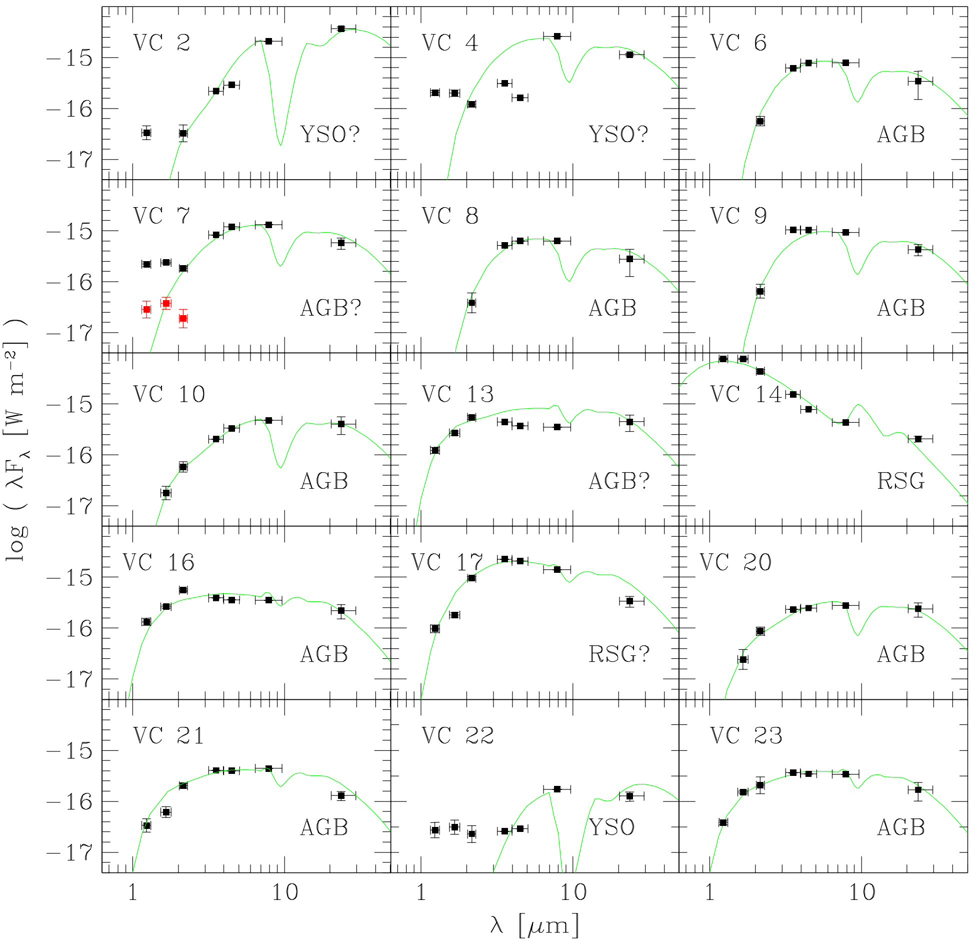

Figure 3. An example of SEDs for stars with 24–μm variability.

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constraints on stellar evolution models and which is a vital ingredient in the much sought–after description of the mass–loss process. Secondly, from observational prospective, this research will gather independent diagnostics of the SFHs of different types of galaxies found in different environments, which help build a comprehensive picture of galaxy evolution in the Local Group. These two reasons together show the unprecedented success of AGB stars in investigating the galaxies formation and evolution.

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