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Assessment of the Tip-AGB Mass-loss Using Synthetic Stellar Samples in the ($M_{\rm Bol}$, J–K) Diagram

Klaus-Peter Schröder[1], Jan Martin Winters[2]

Abstract. A new approach is presented here to interpret the large amount of IR survey data in a most direct and quantitative way, by means of modeling the ($M_{\rm Bol}$, $\rm J-K$) diagram. Combining stellar evolution with dust-driven wind models, we have produced a grid of stellar evolution tracks (for solar abundances) with a mass-loss description for carbon-rich tip-AGB stars derived from the latest version of the self-consistent, pulsating Berlin wind models. By random distribution in age and mass, dependent only on the given IMF, a large synthetic sample of tip-AGB cool giant stars with very strong mass loss has then been generated, including relevant IR properties.

The synthetic cool giant sample presented here is modeled on the solar neighbourhood ($d < 50\,\rm pc$) and its IMF, for 1000× more stars. It provides a detailed inventory of the individual stellar mass loss, the stellar masses (present and initial) and ages. From 5067 giants with B–V > 1.4, only 14 objects are found in their brief (final 30 000 years) superwind phase ($\rm J-K > 6.5$). However, these 14 carbon-rich tip-AGB giants produce more than 1/2 of the collective mass-loss of the whole stellar sample. Since these crucial objects are likely to be under-represented in observed samples, a synthetic sample is required to account for them without bias.

1. Motivation: Why Compute a Synthetic Tip-AGB Stellar Sample?

First of all, dust-enshrouded tip-AGB stars re-inject a major amount of processed stellar material into the interstellar medium.
But: these objects are difficult to observe and to interpret in quantitative terms, obscured by their own mass-loss,
and: several of the most extreme objects are easily missed by IR surveys due to their low flux in J (and K).

Consequently, any quantitative interpretation of observational data (IR surveys) needs the direct comparison with an unambiguous and unbiased theoretical model which predicts individual stellar properties as well as object numbers.

[1]Astronomy Centre, University of Sussex (UK)

[2]MPI für Radioastronomie, Bonn (GER)

2. Input Physics: Evolution Models, IMF, Mass Loss, IR Colours

- Evolution models: computed with a code developed by P.P. Eggleton (1971, 1972, 1973) in Cambridge (UK), with calibrated overshooting (see Pols et al. 1998), and considering the actual mass-loss at each time-step.
- Grid of evolution tracks: fine-meshed, $0.9 < M/M_{\odot} < 16$, mostly with $\Delta M = 0.05 M_{\odot}$, with an onset of overshooting on the ZAMS at $M_i = 1.6 M_{\odot}$, quasi-solar abundances (Z = 0.02), and Reimers-type mass-loss description before reaching the tip-AGB (see Table 1 and Schröder et al. 1999).

Table 1: The characteristics of every 2nd tip-AGB evolution model used in this work: initial stellar mass M_i, mass lost on the RGB, on the AGB (except superwind), by the superwind in the final 30 000 years, and the final stellar mass M_f, all in units of $M_{\odot}$.

M_i	$\int \dot{M}_{RGB}$	$\int \dot{M}_{AGB}$	$\int \dot{M}_{SW}$	M_f	
1.00	0.24	0.20	—	0.55	
1.10	0.12	0.38	0.01	0.56	[1])
1.20	0.09	0.47	0.03	0.58	[1])
1.30	0.08	0.30	0.28	0.60	
1.40	0.07	0.37	0.31	0.61	
1.50	0.06	0.39	0.38	0.62	
1.60	0.05	0.41	0.46	0.63	[2])
1.70	0.04	0.42	0.55	0.63	
1.80	0.03	0.45	0.62	0.64	
1.90	0.02	0.50	0.68	0.65	[3])
2.05	0.001	0.58	0.79	0.66	
2.25	—	0.63	0.92	0.68	
2.50	—	0.67	1.11	0.70	
2.80	—	0.74	1.32	0.72	

[1]) only brief superwind burst(s)
[2]) onset of core overshooting on MS at $M_i \approx 1.6 M_{\odot}$
[3]) RGB evolution ends with He flash for $M_i \leq 1.95 M_{\odot}$

- Distribution of synthetic stars: at random in age; according to an IMF in mass, representative of the solar neighbourhood: $\Delta N_{\mathrm{IMF}}/\Delta \log M_i \propto M^{-1.7}$, with a SFR giving 1000× the number of stars within d < 50 pc (see Schröder & Sedlmayr, 2001).
- The tip-AGB mass-loss (see Fig. 1) is described as a function of stellar properties as derived by Wachter et al. 2001 (see Poster 09.02) from a large number of selected, dust-driven wind models of Winters et al. (2000) for low-mass ($M_i < 3 M_{\odot}$), carbon-rich stars:

$$\log \dot{M} = 8.86 - 1.95 \cdot \log M/M_{\odot} - 6.81 \cdot \log T/\mathrm{K} + 2.47 \cdot \log L/L_{\odot}$$

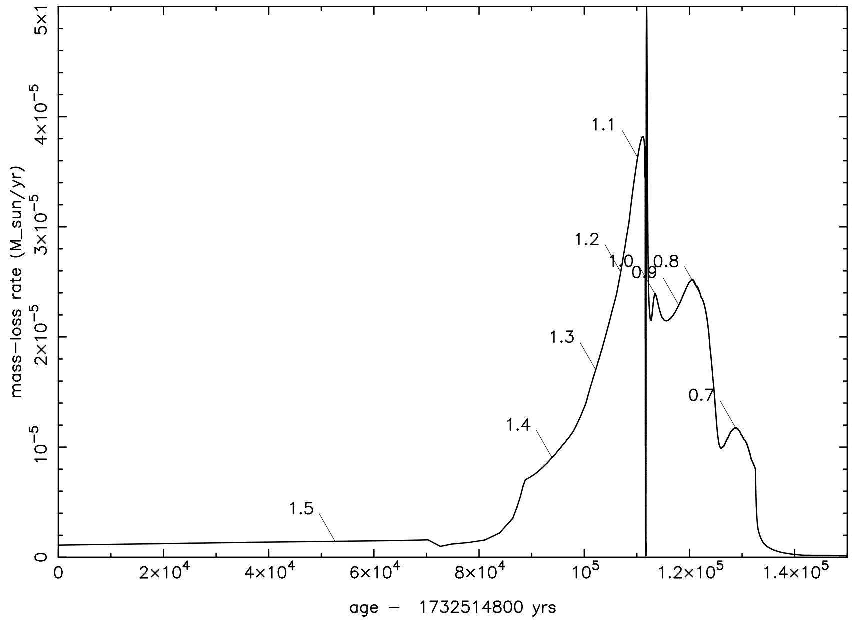

Figure 1. Tip-AGB mass-loss in the final 150 000 yrs of a model with $M_i = 1.85 M_\odot$.

- The relation between mass-loss and an average IR colour (J–K, e.g.) is a complex problem. Therefore, we have derived a synthetic relation from the actual wind model solutions, and we find that it is modified by the individual L/M. With stellar properties given in solar units (and C = 6.9 if $\log \dot{M} < -4.4$; C = 13.8, else):

  $$\mathrm{J} - \mathrm{K} = 9.35 + C \cdot (\log \dot{M} + 4.4) - 10 \cdot (\log L/M - 4.0)$$

  Please note: this means that accurate individual mass-loss rates cannot be derived from observed J − K alone (also, see Table 2)! Instead, a quantitative mass-loss assessment must be carried out on a whole sample of stars of given mass distribution.

With the above approach, the physics of stellar evolution and mass-loss is defined unambiguously, from first-principle astrophysics. The distribution of stars in the generated synthetic sample depends entirely on (i) the IMF, and (ii) reflects precisely the respective evolution time scales encountered with different stellar masses and evolutionary phases.

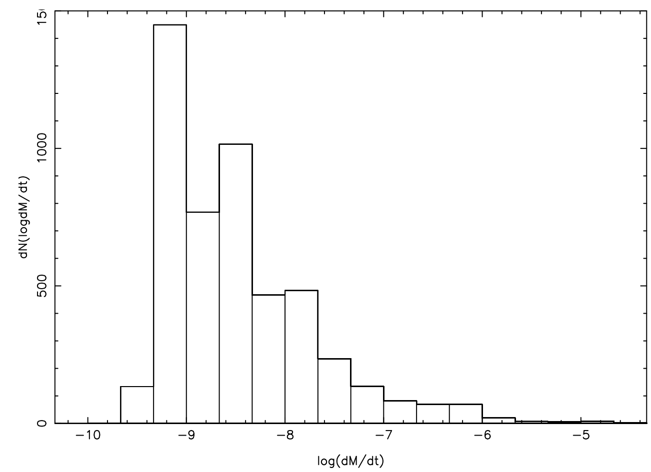

Figure 2. Mass-loss rate distribution of the synthetic giant sample (see text for details)

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3. Results

- We have computed a synthetic stellar sample of giants based on the IMF of the solar neighbourhood and 1000× the number of stars found within 50 pc distance. There is a total of 5067 stars with $\mathrm{B-V} > 1.4$, with a mass-loss ranging between $\approx 10^{-9}$ and $10^{-4} M_\odot$/yr (see Fig. 2).
- In the synthetic sample there are 24 tip-AGB giants with a noticeably enhanced J opacity ($\mathrm{J-K} > 2.5$) caused by their dust-driven, carbon-rich winds, with $\dot{M}$ in excess of $10^{-6} M_\odot$/yr (see Fig. 3 and Table 2). These include 14 dust-enshrouded objects with even $\mathrm{J-K} > 6.5$, which are in their superwind phase (i.e. final 30 000 yrs, with $\dot{M} > 10^{-5} M_\odot$/yr).
- The collective mass-loss of the *synthetic stellar sample* is $5.0 \cdot 10^{-4} M_\odot$/yr. To this, those only 24 stars with $\mathrm{J-K} > 2.5$ contribute $3.5 \cdot 10^{-4} M_\odot$/yr, more than twice as much as the 5043 other giants. Likewise, the 14 superwind objects alone contribute $2.8 \cdot 10^{-4} M_\odot$/yr, i.e., more than half of the collective stellar mass-loss! This result is in excellent agreement with the relative numbers derived *observationally* from a sample of galactic mass-losing AGB stars by Le Bertre et al. (2001).

4. Conclusions

It is possible, on a statistical basis, to compare *directly* observed ($\mathrm{M_{Bol}}$, $\mathrm{J-K}$) diagrams, as being processed from contemporary IR surveys, with computed

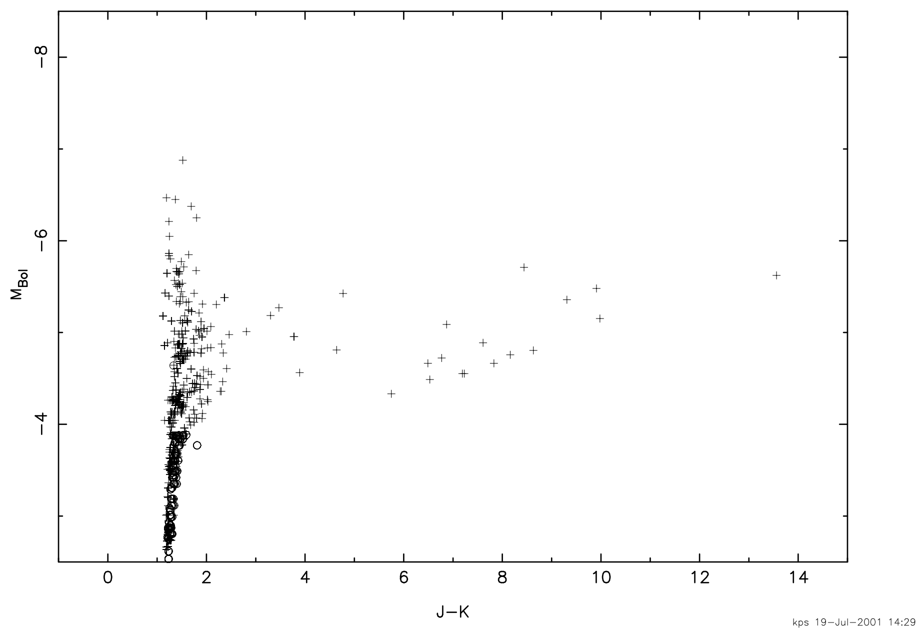

Figure 3. The resulting synthetic (M_{Bol}, J–K) diagram for the synthetic sample. See Table 2 for the properties of the dust-enshrouded, carbon-rich tip-AGB stars with $J - K > 2.5$.

synthetic stellar samples and mass loss. This new approach has a large potential for the quantification of the galactic mass re-injection from cool stellar winds.

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Table 2: Properties of the 24 dust-enshrouded, carbon-rich tip-AGB objects in our synthetic sample with $\mathrm{J}-\mathrm{K} > 2.5$ (see Fig. 3), organized by increasing J–K colour: J–K, mass-loss rate, initial mass, present mass, age, effective temperature and luminosity.

J–K	$\dot{M}[M_\odot/\mathrm{yr}]$	$M_i/M_\odot$	$M_*/M_\odot$	Age/yrs	$T_{\mathrm{eff}}/\mathrm{K}$	$\log L/L_\odot$
2.81	$2.4 \cdot 10^{-6}$	1.748	1.208	$2.001 \cdot 10^{9}$	2422	3.892
3.30	$6.4 \cdot 10^{-6}$	2.021	0.642	$1.442 \cdot 10^{9}$	3421	3.962
3.47	$2.4 \cdot 10^{-6}$	2.259	1.782	$1.113 \cdot 10^{9}$	2605	3.996
3.77	$2.5 \cdot 10^{-6}$	1.830	1.395	$1.732 \cdot 10^{9}$	2563	3.870
3.78	$2.5 \cdot 10^{-6}$	1.833	1.398	$1.731 \cdot 10^{9}$	2563	3.870
3.89	$4.6 \cdot 10^{-6}$	1.543	0.652	$2.663 \cdot 10^{9}$	2928	3.713
4.64	$8.1 \cdot 10^{-6}$	1.736	0.656	$2.005 \cdot 10^{9}$	3022	3.812
4.77	$3.9 \cdot 10^{-6}$	2.474	1.977	$8.244 \cdot 10^{8}$	2636	4.058
5.75	$4.4 \cdot 10^{-6}$	1.213	0.838	$6.496 \cdot 10^{9}$	2552	3.621
6.49	$1.1 \cdot 10^{-5}$	1.669	0.727	$2.353 \cdot 10^{9}$	2731	3.754
6.53	$6.1 \cdot 10^{-6}$	1.307	0.922	$4.869 \cdot 10^{9}$	2524	3.683
6.77	$6.7 \cdot 10^{-6}$	1.556	1.135	$2.662 \cdot 10^{9}$	2525	3.777
6.87	$7.4 \cdot 10^{-6}$	1.949	1.507	$1.533 \cdot 10^{9}$	2544	3.923
7.19	$1.1 \cdot 10^{-5}$	1.476	0.751	$2.971 \cdot 10^{9}$	2542	3.709
7.23	$1.1 \cdot 10^{-5}$	1.483	0.758	$2.971 \cdot 10^{9}$	2542	3.709
7.61	$1.0 \cdot 10^{-5}$	1.674	1.213	$2.353 \cdot 10^{9}$	2476	3.843
7.83	$1.2 \cdot 10^{-5}$	1.406	0.944	$3.754 \cdot 10^{9}$	2438	3.754
8.16	$1.8 \cdot 10^{-5}$	1.678	0.809	$2.167 \cdot 10^{9}$	2483	3.791
8.44	$1.7 \cdot 10^{-5}$	2.757	2.170	$5.978 \cdot 10^{8}$	2565	4.172
8.63	$1.9 \cdot 10^{-5}$	1.476	0.918	$2.971 \cdot 10^{9}$	2403	3.810
9.31	$2.1 \cdot 10^{-5}$	2.547	1.644	$8.250 \cdot 10^{8}$	2497	4.031
9.91	$3.9 \cdot 10^{-5}$	2.463	1.384	$8.251 \cdot 10^{8}$	2377	4.080
9.98	$3.6 \cdot 10^{-5}$	2.158	1.113	$1.265 \cdot 10^{9}$	2377	3.949
13.56	$8.3 \cdot 10^{-5}$	2.656	1.310	$6.996 \cdot 10^{8}$	2333	4.137

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