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Users' Manual for The GRAMS Grid

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1. Introduction

This document is part of the public distribution of the GRAMS models, available from the GRAMS website[1] as a tarball named `grams.tar.gz`. The following files are contained in this archive:

1. `grams_c.tar.gz` – A tarball containing the full published version of the C–rich model grid.
2. `grams_o.tar.gz` – A tarball containing the "original" O–rich grid of 1225 models.
3. `makeogrid.pro` – An IDL code for reconstructing the full published version of the O–rich grid.
4. `README.pdf` – This document.

Sect. 2 describes the GRAMS grid in brief. Sect. 3 explains the luminosity scaling employed in the published version of the GRAMS O–rich grid. A detailed description of the grid data, included as FITS files, is provided in Sect. 4, along with simple IDL commands to extract this information. Finally, Sect. 5 shows how the IDL code `makeogrid.pro` is used

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[1] `http://www.stsci.edu/science/2dust/grams_models.cgi`

to generate the "full" O–rich grid. Appendix A shows how IDL module `SCALEGRAMSGRID` (available in `makeogrid.pro`) can be used to generate luminosity-scaled versions of the grid.

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2. The GRAMS Grid

GRAMS (**G**rid of **R**ed supergiant and **A**symptotic giant **M**odel**S**) is a grid of radiative transfer (RT) models for dust shells around red supergiant (RSG) and asymptotic giant branch (AGB) stars. Radiative transfer models are essential in order to determine the luminosities and mass-loss rates from the spectral energy distributions (SEDs) of red supergiant (RSG) and asymptotic giant branch (AGB) stars. However, calculating individual RT models is time-consuming and becomes impractical for large datasets. In such a case, it is easier instead to compare the SEDs to pre-computed grids of models. Constructed for exactly this purpose, the GRAMS grid allows users to quickly estimate the luminosities and dust mass-loss rates of large numbers of RSG and AGB stars from photometric data.

GRAMS consists of two subsets of models, one each for oxygen-rich (silicate) and carbonaceous dust. Details of the first versions of these grids were described in Sargent et al. (2011) and Srinivasan et al. (2011) respectively. The nature and composition of the dust used in each case was determined from **2D**ust modeling of two O–rich AGB stars (Sargent et al. 2010) and one carbon star (Srinivasan et al. 2010) in the Large Magellanic Cloud (LMC), using photometry and spectra from the SAGE (**S**urveying the **A**gents of **G**alaxy **E**volution; Meixner et al. 2006) and SAGE-Spec (Kemper et al. 2010) programs in conjunction with shorter-wavelength data.

The grid was computed using the code **2D**ust (Ueta & Meixner 2003). **2D**ust is a FORTRAN code that solves the RT equation for axisymmetric dust systems[2]. The current version of the grid consists of spherically symmetric models, but axisymmetric geometries will be considered in the future. **2D**ust was used to solve the RT problem consisting of a model (O–rich or C–rich) AGB photosphere with a dust shell of a given composition, optical depth, and inner and outer radius. The grid was populated by repeating this procedure for different optical depth and inner radius for each photosphere. Models with unrealistic dust temperatures were then filtered out. This procedure resulted in 1225 O–rich models and

[2]More information about **2D**ust can be found in the Users' Manual, available at `http://www.stsci.edu/science/2dust/2dust_manual.pdf.gz`

12 243 C–rich models. The "original" grid of 1225 O–rich models was then mapped onto a larger grid by scaling their luminosities (see Sect. 5 for details), resulting in a total of 68 600 models. For more details about the published version of the GRAMS grid, please consult the GRAMS papers. Please cite these GRAMS publications (Sargent et al. 2011; Srinivasan et al. 2011) if you use the models.

3. Luminosity Scaling

As discussed in Sargent et al. (2011), the "original" GRAMS O–rich grid consists of models with luminosities in the range $1.5{\times}10^3$ – $3.8{\times}10^4$ $L_\odot$. This range does not cover the high-luminosity SAGE-LMC O–rich AGB and RSG candidates. Sargent et al. (2011) addresses this issue by mapping the "original" grid of 1225 models onto 56 luminosities ranging from 10^3 to 10^6 $L_\odot$. In other words, *each model in the original grid is scaled to generate 56 new models*, resulting in a total of 68 600 models in the full grid. The original grid is supplied with this document in FITS format (`grams_o.fits`). The full grid from the paper can be generated by running the enclosed IDL code (`makeogrid.pro`; see Sect. 5 for more details).

Each model in the grid is tagged by various stellar and dust shell parameters. If the luminosity L of a model is changed by a factor s, many of the other parameters associated with the model change. For instance, the flux scales as s. The inner radius $R_{\rm in}$ of the dust shell is specified in the GRAMS models only in terms of the stellar radius, so this fraction remains the same when the luminosity changes. However, the dust mass-loss rate is proportionate to the absolute value of the inner radius and therefore it scales as $\sqrt{s}$.

The luminosity, stellar radius $R_{\rm star}$, the effective temperature $T_{\rm eff}$, the stellar mass $M_{\rm star}$ and the surface gravity g are related according to

$$L \propto R_{\rm star}^2 \, T_{\rm eff}^4 \qquad (1)$$

$$M_{\rm star} \propto g \, R_{\rm star}^2 \qquad (2)$$

While scaling relations for the stellar parameters must satisfy the proportionalities above, Eqns. 1 and 2 are not sufficient to devise a unique way to scale all the parameters. This degeneracy can be broken by taking advantage of the fact that the photospheric spectrum is most sensitive to variations in the effective temperature and surface gravity. These parameters are, therefore, left unchanged after scaling. These constraints, in addition to Eqns. (1) and (2) above, provide us with enough information to scale the remaining parameters. Table 1 summarizes these scaling relations.

Table 1. Scaling relations for various stellar and dust shell parameters

Parameter	Scale factor[a,b]
L ($L_\odot$)	s
$T_{\rm eff}$ (K)	–
$R_{\rm star}$ ($R_\odot$)	$\sqrt{s}$
$\log g$[cm s^{-1}]	–
Z	–
$M_{\rm star}$ ($M_\odot$)	s
F_ν (Jy)	s
$R_{\rm in}$ ($R_{\rm star}$)	–
$T_{\rm in}$	–
$\dot{M}_{\rm dust}$	$\sqrt{s}$

[a]A dash implies that the parameter is not scaled

[b]The absolute value of $R_{\rm in}$ scales as $\sqrt{s}$, but the GRAMS grid only specifies $R_{\rm in}$ in terms of $R_{\rm star}$.

An important caveat for the user is that not all the scaled models may be realistic representations of AGB or RSG stars. Depending on the scale factors picked to generate a larger grid, some models may even be unphysical. The user must therefore be careful when interpreting the parameters predicted by such scaled models (for example, when the enclosed IDL code generates the full grid from Sargent et al. (2011), some of the scaled $M_{\rm star}$ values are too high or too low). In general, the scaled luminosity and dust mass-loss rate are the most reliable of the parameters, so in such cases the derived L and $\dot{M}_{\rm dust}$ estimates may still be reasonable.

The luminosity range of the GRAMS C–rich models range approximately from 1100 $L_\odot$ to 26 000 $L_\odot$. As only a small number carbon stars are observed outside this range, the grid published in Srinivasan et al. (2011) does not employ luminosity scaling. If needed, the `SCALEGRAMSGRID` module contained in the IDL code `makeogrid.pro` can be used for this purpose (see Appendix A).

4. The GRAMS grid in FITS Format

The FITS files provided with this distribution contain the original O–rich grid and the full C–rich grid. The data for each is stored as an array of structures (one structure per model). In both cases, the structures contain the following fields:

1. `teff` – The effective temperature of the model photosphere in K.
2. `logg` – $\log_{10}$[surface gravity in cm s^{-2}].
3. `mass` – Stellar mass in solar units.
4. `c2o` – Photospheric C/O ratio (set to `-99` for O–rich models).
5. `rin` – Inner radius of the dust shell in terms of stellar radius.
6. `tau1` – Optical depth at 1 μm.
7. `tau10 (tau11_3)` – Optical depth at 10 μm (11.3 μm) for O–rich (C–rich) models.
8. `lum` – Luminosity in solar units.
9. `mlr` – Dust mass-loss rate in $M_\odot$ yr^{-1}.

10. `fphot` – Flux in Jy at LMC distance in the UBVI, JHK_s, IRAC, MIPS, AKARI and WISE filters[3].

11. `mphot` – Magnitude in the above filters.

12. `tin` – Dust temperature at inner shell radius in K.

13. `lspec` – Spectral grid wavelengths in μm.

14. `fspec` – **2D**ust output spectrum in Jy at LMC distance.

The array of structures can be loaded into a variable using the IDL routine `MRDFITS` as follows:

```
IDL> ogrid = MRDFITS('ogrid_parent.fits',1,header)
```

The header summarizes a lot of useful information about the grid, as well as the order of storage of the synthetic photometry in various broadband filters. Once the variable `ogrid` is created, the individual fields can be easily accessed. For example:

```
IDL> PRINT,ogrid[10].teff
```

will print the effective temperature of the 11th model photosphere,

```
IDL> PRINT,ogrid[10].fphot[10]
```

prints the IRAC 8 μm flux[4] in Jy of the 11th model, and

```
IDL> PLOT,ogrid[10].lspec,ogrid[10].fspec,/XL,/YL,XRA=[.3,30],XSTY=1
```

will plot the **2D**ust output spectrum of the 11th model.

5. Generating the Full O–rich Grid using `makeogrid.pro`

The code `makeogrid.pro`, included with this distribution, should be used to generate the published version of the O–rich grid. The necessary IDL instructions are as follows. **Note that this code invokes the routine `CMREPLICATE` which is available as part of Craig Markwardt's IDL library**[5].

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[3] For information on the central wavelengths and flux zeropoints of these filters, see Sargent et al. (2011) and Srinivasan et al. (2011) and references therein.

[4] See the FITS header for the order of storage of the broadband filters.

[5] `http://www.physics.wisc.edu/~craigm/idl/down/cmreplicate.pro`

After compiling the code, type:

```
IDL> makeogrid,FITSFILE='output.fits'
```

The full grid is then written to the file `output.fits`. The output FITS file is structurally similar to the input file, differing only in the number of entries (models) and the associated parameter values (the header information is transferred from the original file). Leaving out the FITSFILE keyword sends the output to a file named `ogrid_full.fits`.

A. Luminosity Scaling Using The SCALEGRAMSGRID Module

The published version of the O–rich grid contains a large number of models that span the entire range of the parameter space (e.g., near- and mid-infrared colors) expected for RSG and AGB stars, but there are only 56 unique luminosities – gridded logarithmically from 10^3 $L_\odot$ to 10^6 $L_\odot$– due to the luminosity scaling procedure used in the paper (and, consequently, in `makeogrid.pro`). While this was sufficient to demonstrate the general agreement between the models and SAGE data, a specific application may require a different scaling approach. The `SCALEGRAMSGRID` module available in `makeogrid.pro` can be used for this purpose. This module accepts a structure of "parent" models which is then mapped onto a final grid, by using one of two possible scaling methods: each "parent" model can be either scaled by using the same set of scale factors, or it can be scaled to the same set of luminosities (The published version of the grid uses this option).

For instance, if the luminosity of each model is to be scaled to half the original value and twice the original value, while also including the original luminosity in the final grid, the following command can be used[6]:

```
IDL> scalegramsgrid,parent,final,SCALE=[0.5,1.0,2.0]
```

The scaled grid in this case will have thrice as many models as the parent grid, and it will be stored in the variable `final`, which can be written to a FITS file using the `MWRFITS` routine if required. Sometimes, it may be useful to have all models scaled to the same luminosity representing a "typical" star. For a luminosity of 3000 $L_\odot$, this can be accomplished by typing

```
IDL> scalegramsgrid,parent,final,LUM=[3000.]
```

If, instead, the user requires that all the models be mapped onto luminosity values contained

[6]It is assumed that the code `makeogrid.pro` has already been compiled.

in an array named `lums`, the command would be:

```
IDL> scalegramsgrid,parent,final,LUM=lums
```

The above command is used by the `MAKEOGRID` module to generate the published version of the O–rich grid.

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