

## THEORETICAL ISOCHRONES IN THE OBSERVATIONAL PLANE OF THE VILNIUS PHOTOMETRIC SYSTEM

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**Abstract.** Theoretical isochrones for the initial chemical composition [ $Z=0.0004$ ,  $Y=0.23$ ], [ $Z=0.004$ ,  $Y=0.24$ ], [ $Z=0.008$ ,  $Y=0.25$ ] and [ $Z=0.02$ ,  $Y=0.28$ ] and ages in the range  $4 \cdot 10^6$  yr to  $16 \cdot 10^9$  yr are presented in the observational plane of the Vilnius photometric system. The isochrones have been calculated from stellar models computed with the most recent radiative opacities by Iglesias et al. (1992) using the same procedure as described by Bertelli et al. (1994). All stellar models were followed from the zero age main sequence (ZAMS) to the central carbon ignition for massive stars or to the beginning of the thermally pulsing regime of the asymptotic giant branch phase (TP-AGB) for low and intermediate mass stars. For each isochrone, we give the current mass, effective temperatures, bolometric and visual magnitudes,  $U-P$ ,  $P-X$ ,  $X-Y$ ,  $Y-Z$ ,  $Z-V$  and  $V-S$  color indices of the Vilnius photometric system and the luminosity function for the case of the Salpeter law.

**Key words:** stars: evolution, HR diagram, isochrones – open clusters: individual: M 67

### 1. INTRODUCTION

Complete and accurate grids of stellar isochrones are the starting point of many astrophysical applications, e.g. studies of open and globular clusters, interpretation of the integrated photometric

and spectral properties of stellar systems, chemical and dynamical evolution of galaxies, etc.

Recently, a new library of stellar evolution models with a homogeneous physical input and a complete coverage of the mass range and major evolutionary phases has been calculated by Alongi et al. (1993), Bressan et al. (1993) and Fagotto et al. (1994a,b). The models were computed with the most recent radiative opacities by Iglesias et al. (1992) assuming a mild convective overshoot from the central cores and external envelopes, the effects of mass-loss by stellar wind and the evolution of chemical abundances of sixteen elements.

The seven-color Vilnius photometric system makes it possible to obtain spectral classes, luminosities, metallicities and interstellar reddening to very faint stars at large distances from the Sun. No other photometric system, currently in use, can do this type of work in the presence of interstellar reddening for all spectral classes. The Vilnius system can work without difficulty in the areas of considerable interstellar reddening, such as galactic spiral arms, interarm regions and the central bulge.

In this paper, isochrones in the observational plane  $M_V, (Y - V)_0$  of the Vilnius photometric system are presented for the first time. We think that the possibility to determine stellar ages using this photometric system will be useful and will make this system even more applicable.

## 2. STELLAR MODELS AND TECHNIQUE OF ISOCHRONE CALCULATION

The isochrones have been constructed by means of the same procedure as described by Bertelli et al. (1994), so the presentation will be limited to a few relevant points of their input physics and main characteristics.

Complete evolutionary isochrones have been computed for the ages in the range  $4 \cdot 10^6$  yr to  $16 \cdot 10^9$  yr and initial chemical compositions  $[Z=0.0004, Y=0.23]$ ,  $[Z=0.004, Y=0.24]$ ,  $[Z=0.008, Y=0.25]$  and  $[Z=0.02, Y=0.28]$  on a basis of evolutionary sequences by Bressan et al. (1993) and Fagotto et al. (1994a, b). The choice of the chemical composition parameters  $Y$  and  $Z$  was made according to the law  $\Delta Y / \Delta Z = 2.5$  which represents a lower limit to the estimates given by Pagel (1989).

For low mass stars, the tracks from the main sequence up to the tip of RGB, and from the beginning of the core He-burning phase

up to the start of the thermally pulsing regime of the He-burning shell (TP-AGB) are computed separately. This allows to avoid the complicated evolution from the stage of He-flash down to the horizontal branch (HB) and easily incorporate the effect of mass-loss in the RGB stage on the location of models on the Zero Age Horizontal Branch (ZAHB).

The extension of the convective regions, either cores or envelopes, is determined in the presence of the convective overshoot. Overshoot from the convective cores is calculated according to Bressan et al. (1981), whereas that from the convective envelopes according to Alongi et al. (1991).

The mixing length parameter in the outer most super-adiabatic convective region of the envelope is taken  $1.63 \times H_P$ , so that the model with the solar chemical composition and age should fit luminosity and effective temperature of the Sun.

For the stars with the initial masses between  $12 M_\odot$  and  $120 M_\odot$ , evolutionary models are computed taking into account the mass-loss according to the rates by de Jager et al. (1988) from the main sequence up to the so-called de Jager limit in the HR diagram. The rates also include the mass-loss dependence on metallicity from Kudritzki et al. (1989). Beyond the de Jager limit, the mass-loss rate is increased to  $10^{-3} M_\odot \text{ yr}^{-1}$ , as suggested by observations of the luminous blue variables. For Wolf-Rayet stars the rates are according to Langer (1989).

### *2.1. Chemical elements, nuclear reaction rates and neutrino losses*

For the solar metallicity, the initial abundance of the elements heavier than helium is taken from Grevesse (1991). When varying metallicity, the initial abundances of these elements are changed keeping their relative proportions as in the Grevesse (1991) compilation. In all cases, care has been taken to secure that the abundances are the same as in the computations of the radiative opacities. The reference solar metallicity is  $Z_\odot = 0.020$ .

To translate from  $[\text{Fe}/\text{H}]$  to  $Z$  and viceversa, we derived the following formula, which also takes into account the variation of the initial hydrogen content with the metallicity

$$[\text{Fe}/\text{H}] = \log(Z/X) + 1.574,$$

where we adopt a ratio  $Z_{\odot}/X_{\odot} \simeq 0.02667$  (Anders & Grevesse 1989) and recall that the above models are computed with a solar partition of heavy elements.

Nuclear energy generation rates are taken from Caughlan & Fowler (1988) including the  $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$  reaction of the He-burning stage. The rates of neutrino emissions are taken from Munakata et al. (1985).

## 2.2. Opacities

Radiative opacities are taken from Iglesias et al. (1992) including the spin-orbit interaction in the treatment of Fe atomic data. The solar photospheric iron abundance is from Grevesse (1991) and Hannaford et al. (1992). An important improvement of the new opacity tabulations, with respect to these by Huebner et al. (1977), is given by the finer grid adopted in the temperature-density plane, which permits a better accuracy in the interpolation technique.

Since the opacity tables by Iglesias et al. (1992) do not extend below 6000 K and above  $10^8$  K, the opacities at lower and higher temperatures are taken from Huebner et al. (1977) and Cox & Stewart (1970a,b).

Finally, the contribution to the opacity by CN, CO, H<sub>2</sub>O and TiO molecules is included by means of the analytical relationships by Bessell et al. (1989, 1991), based on the tabulations by Alexander (1975) and Alexander et al. (1983).

## 2.3. Conversion from theoretical to observational plane

Theoretical luminosities and effective temperatures along the isochrones are translated to absolute magnitudes and colors using extensive tabulations of bolometric corrections (*BC*) and colors obtained by convolution of the spectral energy distributions (SEDs) contained in the library of synthetic stellar spectra kindly made available by Kurucz (1992, private communication) and the response functions of the photometric passbands (see Table 1), which have been taken from Straižys (1992).

Since Kurucz SEDs are not accurate enough for M stars (Kurucz 1992, Malagnini et al. 1992), we have adopted the empirical SEDs for the coolest stars as described by Bertelli et al. (1994).

**Table 1.** Mean wavelengths and half-widths of passbands of the Vilnius photometric system.

| Passband             | <i>U</i> | <i>P</i> | <i>X</i> | <i>Y</i> | <i>Z</i> | <i>V</i> | <i>S</i> |
|----------------------|----------|----------|----------|----------|----------|----------|----------|
| $\lambda_0$ (nm)     | 345      | 374      | 405      | 466      | 516      | 544      | 656      |
| $\Delta\lambda$ (nm) | 40       | 26       | 22       | 26       | 21       | 26       | 20       |

In calculation of synthetic color indices, the following normalization was accepted:  $U - P = P - X = X - Y = Y - Z = Z - V = V - S = 0$  for O8 spectral type stars.

Finally, the zero point of the bolometric corrections is fixed by imposing that for the Kurucz model of the Sun  $BC = -0.08$  (Bessell 1983).

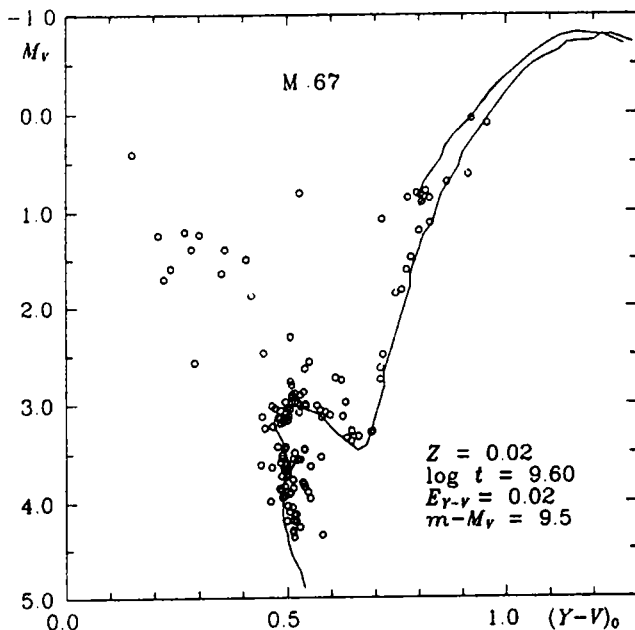
#### 2.4. Electronic data-base of isochrones

The electronic catalog consists of Tables 1 to 4, each one corresponding to a different helium content  $Y$  and metallicity  $Z$ . Each isochrone is labelled by the age (logarithmic value in years) and the chemical parameters. The evolutionary isochrones are available on request.

For each isochrone, the following quantities are listed: column 1 gives the current mass in solar units along the isochrone; column 2 gives logarithm of the effective temperature; column 3 gives the bolometric magnitude; column 4 gives the absolute visual magnitude in the Vilnius system; columns 5 to 11 give the color indices  $U - P$ ,  $P - X$ ,  $X - Y$ ,  $Y - Z$ ,  $Z - V$ ,  $V - S$  and  $Y - V$ ; column 12 gives the luminosity function for the case of the Salpeter law.

### 3. COMPARISON OF ISOCHRONES WITH OBSERVATIONAL DATA FOR THE OPEN CLUSTER M 67

The old open cluster M 67 was observed in the Vilnius photometric system both photoelectrically (K. Černis, published in Straižys & Kazlauskas 1993) and by CCD techniques (Boyle et al. 1995). In plotting the  $M_V, (Y - V)_0$  diagram, we accepted the interstellar reddening  $E_{B-V} = 0.03$  mag, obtained by Nissen et al. (1987) and confirmed recently by Carraro et al. (1996). This value corresponds to  $E_{Y-V} = 0.02$  mag. The distance modulus  $V - M_V = 9.5$  was accepted from Anthony-Twarog (1987). We considered the cluster to



**Fig. 1.** The  $M_V, (Y-V)_0$  diagram of the open cluster M 67 together with the isochrone of  $4 \cdot 10^9$  yr and  $Z = 0.02$ .

be of solar metallicity, according to Nissen et al. (1987) and Hobbs & Thorburn (1992).

Fig. 1 displays the data for M 67 together with the isochrone of  $4 \cdot 10^9$  yr and  $Z = 0.02$ . The same age was obtained for this cluster by Meynet et al. (1993), Dinescu et al. (1995) and most recently by Carraro et al. (1996).

Until now, 25 open clusters have been observed in the Vilnius system according to the “General photometric catalogue of stars observed in the Vilnius system” (Straizys & Kazlauskas 1993). Some of them are located in the areas of a considerable interstellar reddening. The determination of their ages is a subject for our future work.

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## REFERENCES

- Alexander D. R. 1975, *ApJS*, 29, 363
- Alexander D. R., Johnson H. R., Rympa R. L. 1983, *ApJ*, 272, 773
- Alongi M., Bertelli G., Bressan A., Chiosi C. 1991, *A&A*, 244, 95
- Alongi M., Bertelli G., Bressan A., Chiosi C., Fagotto F., Greggio L., Nasi E. 1993, *A&AS*, 97, 851
- Anders E., Grevesse N. 1989, *Geochimica et Cosmochimica Acta*, 53, 197
- Anthony-Twarog B. J., Payne D. M. Twarog B. A. 1989, *AJ*, 97, 1048
- Bartkevičius A., Sperauskas J. 1983, *Bull. Vilnius Obs.*, No. 63, 3
- Bertelli G., Bressan A., Chiosi C., Fagotto F., Nasi E. 1994, *A&AS*, 106, 275
- Bessell M. S. 1983, *PASP*, 95, 480
- Bessell M. S., Brett J. M., Scholz M., Wood P. R. 1989, *A&AS*, 77, 1
- Bessell M. S., Brett J. M., Scholz M., Wood P. R. 1991, *A&AS*, 87, 621
- Boyle R. P., Straizys V., Vrba F. J., Smriglio F., Dasgupta A. K. 1995, in *New Developments in Array Technology and Applications (IAU Symp. No. 167)*, ed. A. G. Davis Philip, K. A. Janes & A. R. Upgren, Kluwer Academic Publishers, Dordrecht, p. 363
- Bressan A., Bertelli C., Chiosi C. 1981, *A&A*, 102, 25
- Bressan A., Fagotto F., Bertelli G., Chiosi C. 1993, *A&AS*, 100, 647
- Carraro G., Girardi L., Bressan A., Chiosi C. 1996, *A&A*, 305, 849
- Caughlan G. R., Fowler W. A. 1988, *Atomic Data and Nucl. Data Tables*, 40, 283
- Cox A. N., Stewart J. N. 1970a, *ApJS*, 19, 243
- Cox A. N., Stewart J. N. 1970b, *ApJS*, 19, 261
- Fagotto F., Bressan A., Bertelli G., Chiosi C. 1994a, *A&AS*, 104, 365
- Fagotto F., Bressan A., Bertelli G., Chiosi C. 1994b, *A&AS*, 105, 29
- Dinescu D. I., Demarque P., Guenther D. B., Pinsonneault M. H. 1995, *AJ*, 109, 2090
- Grevesse N. 1991, *A&A*, 242, 488
- Hannaford P., Lowe R. M., Grevesse M., Noels A. 1992, *A&A*, 259, 301
- Hobbs L. M., Thorburn, J. A. 1992, *AJ*, 104, 669
- Huebner W. F., Merts A. L., Magee N. H., Argo M. F. 1977, Los Alamos Scientific Laboratory Report, LA-6760-M
- Iglesias C. A., Rogers F. J., Wilson B. G. 1992, *ApJ*, 397, 717
- de Jager C., Nieuwenhuijzen H., van der Hucht K. A. 1988, *A&AS*, 72, 259
- Kudritzki R. P., Pauldrach A., Puls J., Abbott D. C. 1989, *A&A*, 219, 205
- Kurucz R. L. 1992, in *Stellar Populations of Galaxies*, eds. B. Barbuy & A. Renzini, Kluwer Academic Publishers, Dordrecht, p. 225
- Langer N. 1989, *A&A*, 210, 93

- Malagnini M. L., Morossi C., Buser R., Parthasarathy M. 1992, *A&A*, 261, 558
- Meynet G., Mermilliod J.-C., Maeder A. 1993, *A&AS*, 98, 477
- Munakata H., Kohyama Y., Itoh N. 1985, *ApJ*, 296, 197
- Nissen P. E., Twarog B. A., Crawford D. L. 1987, *AJ*, 93, 634
- Pagel B. E. J. 1989, in *Evolutionary Phenomena in Galaxies*, eds. J. Beckman & B. E. J. Pagel, Cambridge University Press, p. 201
- Straizys V. 1992, *Multicolor Stellar Photometry*, Pachart Publ. House, Tuscon, Arizona
- Straizys V., Kazlauskas A. 1993, *General Photometric Catalogue of Stars Observed in the Vilnius System*, *Baltic Astronomy*, 2, 1