Astronomy for Developing Countries
IAU Special Session at the 24th General Assembly, 2001
Alan H. Batten, ed.

The Role of Astronomical Catalogues in Modern Theory and Observation

Oleg Yu. Malkov, Alexander V. Tutukov, Dana A. Kovaleva

Institute of Astronomy, 48 Pyatnitskaya St., Moscow 109017, Russia.
e-mail: malkov@inasan.rssi.ru

Abstract. Astronomical catalogues are powerful tools for carrying out modern theoretical and observational studies. Analysis of catalogue data enables important information to be obtained and does not require modern expensive observational techniques to reach reliable scientific results. In this paper we give some examples of such approaches and present some results of successful work with catalogues.

1. Introduction

Astronomical catalogues represent an important branch of modern astronomy. Besides their obvious use as lists of positions, photometry and other data for celestial objects, the great feature of astronomical catalogues is their effectiveness as powerful tools to carry out modern theoretical and observational studies. About 1000 modern astronomical catalogues accumulate accessible information on the principal astronomical objects: stars, galaxies and now extrasolar planets. Many astronomical centres in the world are involved in compilation and accumulation of catalogues; and maintain sets of astronomical catalogues in archives that are publicly accessible (by means of standard Internet tools).

Any stellar catalogue can be considered as a product of the history of star formation, the consequent stellar evolution, and observational selection effects. Therefore, astronomical catalogues offer an exceptional opportunity for highly effective investigations of stellar evolution, provided that we can correctly take into account the effects of observational selection and present reliable ideas about history of star formation. Analysis of catalogue data enables important information about the evolution of stars and other astronomical objects to be obtained. Such analysis does not require modern expensive observational techniques to reach reliable scientific results. In this paper we give some examples of such approaches and present some results of successful work with catalogues in the Institute of Astronomy of the Russian Academy of Sciences.

2. Study of Physical Properties of Binary Stars

The data for about 1000 spectroscopic and about 3000 visual binaries provide an opportunity to derive the birth-function of binary stars in our Galaxy. This birth-function gives the formation rate of binary stars as a function of the primary mass, of the components' mass-ratio and of the major semi-axis. Analysis

https://doi.org/10.1017/S0251107X00000961 Published online by Cambridge University Press

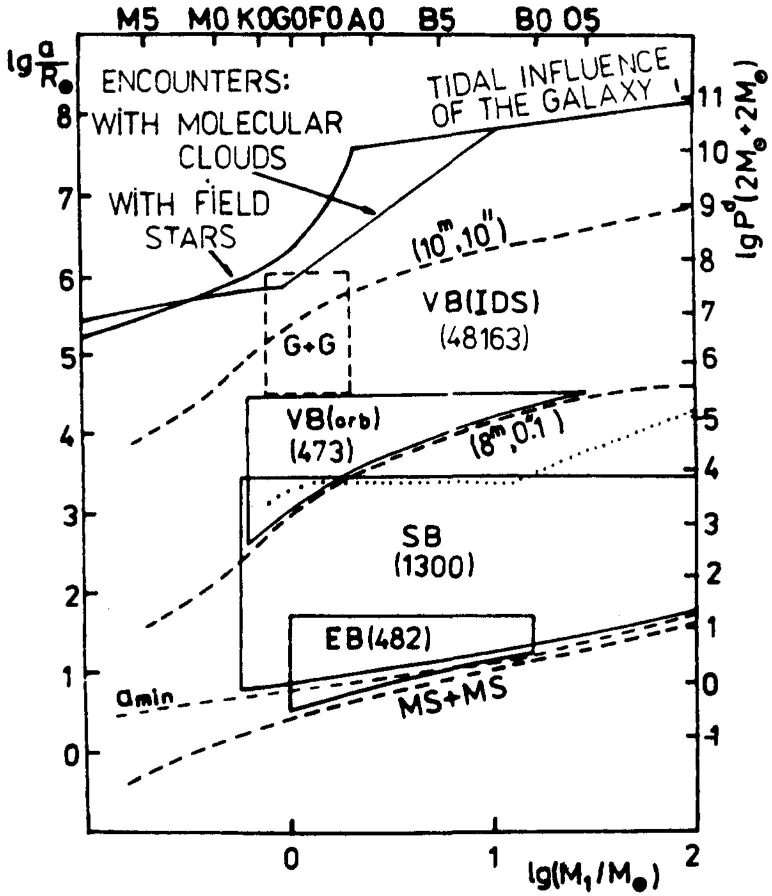

Figure 1. Position of binary stars of different types in log(primary mass) — log(linear separation) diagram. EB: eclipsing binaries, SB: spectroscopic binaries, VB: visual binaries, VB(orb): VB with known orbits. The MS+MS line indicates the lowest lomit of separations set in by the contact of two homogeneous stars. The line a_{min} shows the minimal separation for new-born stars. Thick lines in the upper part of the diagram indicate the maximum major semi-axes of binary orbits. The region G+G is occupied by VB with giant components. The dotted line limits the region of evolutionary close binaries.

https://doi.org/10.1017/S0251107X00000961 Published online by Cambridge University Press

of the distribution over orbital angular momentum made it possible to estimate the number of planetary systems in our Galaxy. The birth-function and current theory of evolution of binary stars helped to compile the numerical scenario program for study of evolution of binary stars. This program reproduces the current population of binaries and provides the possibility of comparing the main properties of the model and observations. Reasonable agreement with the observations gives good grounds for believing in all the included ingredients. The complex of investigations of binary stars provides a good example of current evolutionary population approach to astronomical catalogues.

This work is based on the data from the following catalogues: *Index Catalogue of Visual Double Stars* (Jeffers, van den Bos, & Greeby 1963), *Catalogue of Physical Parameters of Spectroscopic Binary Stars* (Kraicheva et al. 1980), *The Fourth Catalog of Orbits of Visual Binary Stars* (Worley & Heintz 1983), *Eighth Catalogue of the Orbital Elements of Spectroscopic Binary Systems* (Batten, Fletcher, & McCarthy 1989), *The Washington Visual Double Star Catalog* (Worley & Douglass 1996). The position of binary stars of different types in $\log m_1$ — $\log a$ plane is presented in Figure 1.

3. Analysis of Properties and Evolution of Extra-Solar Planets

Another example of the application of astronomical data to the analysis of the physical properties and evolution of astronomical objects is the quickly growing catalogue of extra-solar planets (Tutukov, unpublished). Several dozens of them were discovered during last years. Figure 2 shows these planets, together with planets of the solar system: the major semi-axes of the orbits are plotted against the mass of the respective central star. There are several important lines plotted as well. "The edge" shows the external border of planetary systems with external planets forming through collision in the lifetime of the central star for stars with masses above the solar mass and during the Hubble time for systems with with central stars of a lower mass. The lines "$T_d = 1500K$" and "$T_d = 180K$" indicate isotherms. Dust in the region with $T_d > 1500K$ will be evaporated, thus excluding planet formation. Dust in $T_d \leq 180K$ can have ice envelopes, and planets formed of such dust will have powerful gas envelopes.

It is evident now that planets can exist only in the area between the lines "the edge" and "$T_d = 1500K$". Observations support this evident prediction. The most part of known planets are concentrated around stars of solar mass. This result is a simple consequence of an evident effect of observational selection. Stars with masses above $1.5m_\odot$ are quick rotators with wide spectral lines. This practically excludes the search for velocity variability of very low amplitudes. MS stars with masses much below the solar mass are faint because of selection effects, and their variability is also undetectable. Therefore solar-mass stars are the best candidates to search for radial-velocity variability since they are bright enough and have very narrow lines in their spectra.

4. Large Catalogues Data-Retrieval Software

Large astronomical catalogues, containing astrometric and photometric information for millions of objects are widely used by the astronomical community

https://doi.org/10.1017/S0251107X00000961 Published online by Cambridge University Press

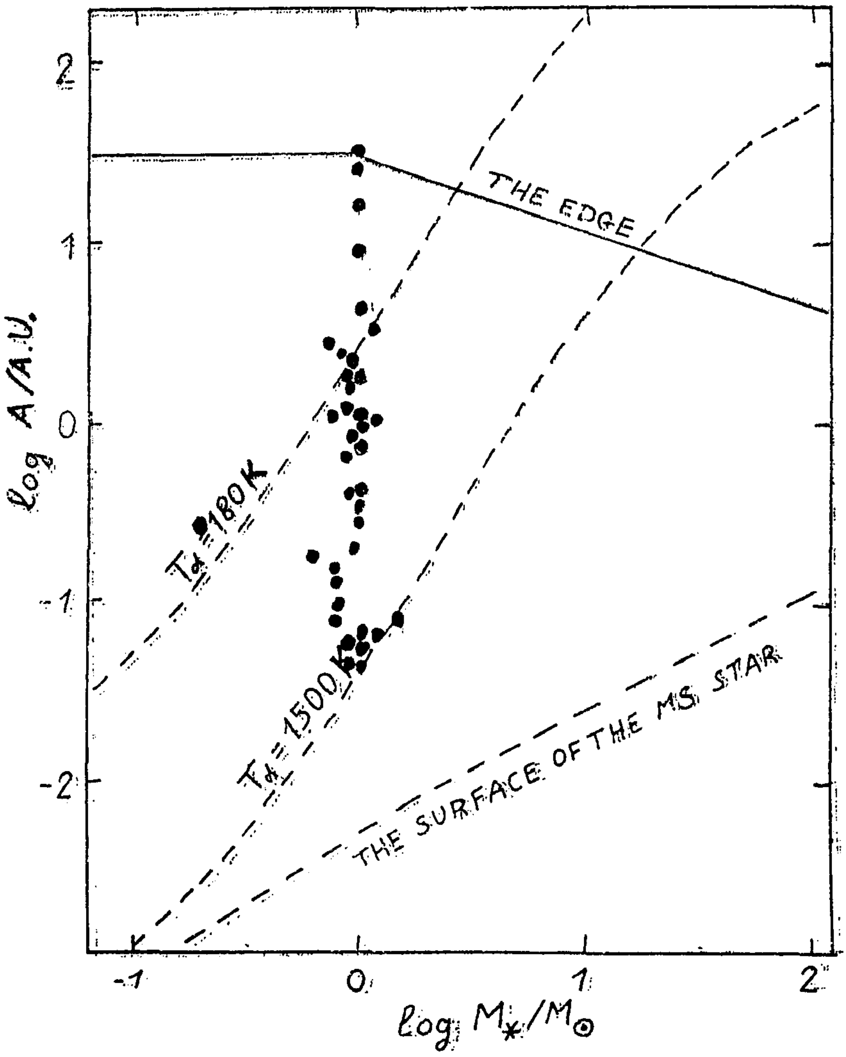

Figure 2. Position of planets in the plane (mass of the central-star – major semi-axis of the orbit). The meaning of lines is explained in the text.

https://doi.org/10.1017/S0251107X00000961 Published online by Cambridge University Press

for all sorts of applications, particularly, for preparing and carrying out observations with ground-based and space-based telescopes, for quick identification of objects and first interpretation of results. Among these catalogues are the *Guide Star Catalog (ver 1.1)*, hereafter GSC (Lasker et al. 1990, Russell et al. 1990, Jenkner et al. 1990) and *USNO Catalog of Astrometric Standards* family, hereafter USNO-A (Monet 1996). However, getting at the actual catalogue data is not quite straightforward, due to the huge size of the catalogues and a somewhat complicated internal format. To facilitate data retrieval, user-friendly programs have been created for GSC (Malkov & Smirnov 1995) and for USNO-A (Malkov & Smirnov 1999) that let one look directly at the data in the large catalogues, either as a graphical sky map, a plot, or a simple text table. The programs can read a sampling of the catalogue data for a given sky region, store this sampling in a text file, and display a graphical map of the sampled region.

We have also designed XSKYMAP — a widget-based IDL application for visualization of astronomical catalogues. XSKYMAP (Smirnov & Malkov 1999) supports the ZGSC — a compressed version of the GSC that was constructed by Smirnov & Malkov (1997). ZGSC employs a custom binary format and an adaptive compression algorithm to achieve 6:1 lossless compression of GSC — down to about 200 Mb (from 1.2 Gb). XSKYMAP also supports the *PPM* family of astrometric catalogues, namely the *Catalog of Positions and Proper Motions*, the *Catalog of Positions and Proper Motions – South*, the *Bright Stars Supplement* to the *PPM* and *PPM South Catalog*, (Revised Edition), and the *90000 Stars Supplement* to the *PPM Star Catalog* (Roeser & Bastian 1988; Roeser & Bastian, 1993; Roeser, Bastian, & Kuzmin 1993). GSC's inherent depth of field is supplemented by extremely precise positions of relatively brighter stars from the *PPM*.

XSKYMAP provides a wide range of visualization tools for various applications. The current version has been integrated with the control software for the Galileo Italian National Telescope as an observational support tool (Pasian et al. 1998); the primary applications being generation of finder charts and preliminary telescope positioning.

5. Testing the Galaxy Model with the Guide Star Catalog

In another project we planned to develop methods of using the *GSC* as a source of statistical data, and apply them to the Bahcall-Soneira Galaxy model (Bahcall & Soneira 1980), with the aim of testing and extending the latter into lower galactic latitudes. A secondary goal is a detailed investigation of the photometric and statistical properties and irregularities of the *GSC*, as well as development of methods and software to deal with them. We modified the Bahcall-Soneira system to produce results in the native photometric bands of the *GSC*. We used our programs to extract *GSC* data sets from 40 small regions evenly distributed across the sky. To avoid dealing with blurred plate edges and plate overlaps at this stage, each area was shifted to the nearest plate centre, and the effective radius decreased to leave out any irregularities. To compare the *GSC* star counts with the theoretical model distributions, we developed a suite of IDL programs, and performed standard statistical tests (χ^2, Kolmogorov-Smirnov).

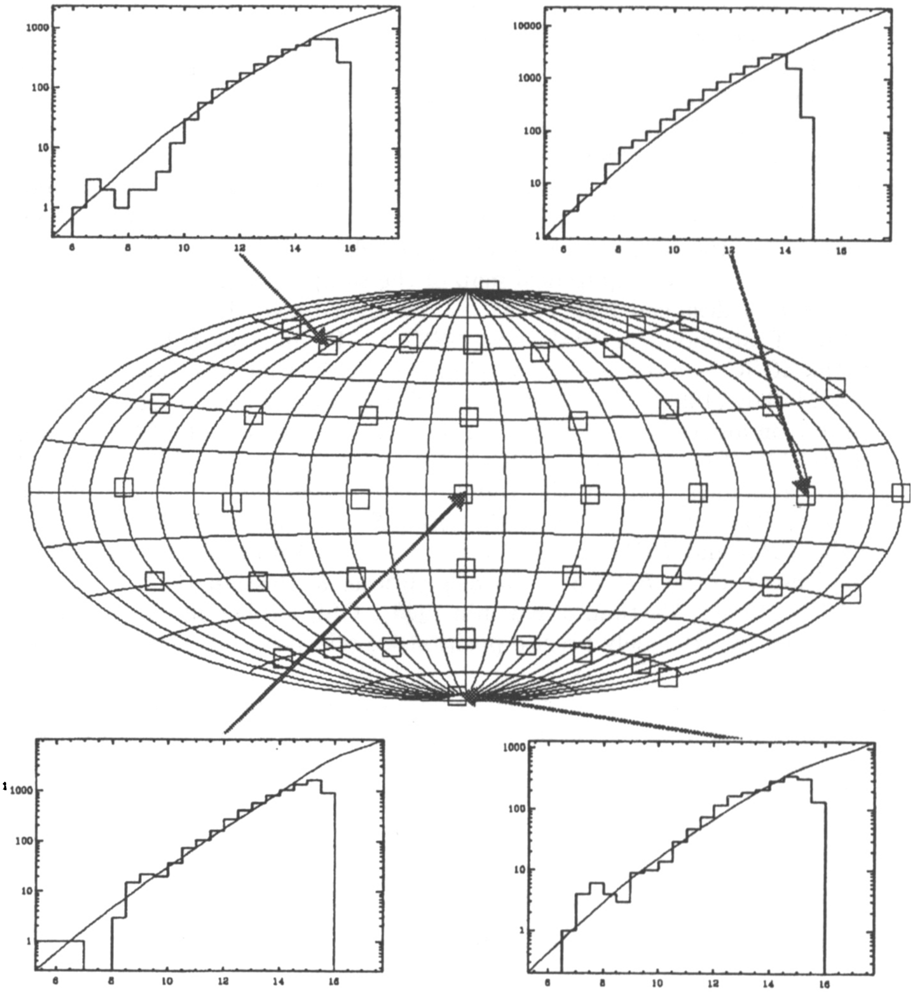

Figure 3. Comparison of the Bahcall-Soneira Galaxy model (curves) with the GSC data (histograms) for some areas from a set uniformly distributed across the sky

https://doi.org/10.1017/S0251107X00000961 Published online by Cambridge University Press

Initial statistical comparisons between theoretical star counts and those obtained from the *GSC* (see Figure 3) showed interesting and sometimes significant discrepancies, namely: a deficit of bright stars ($11^m - 12^m$) in the *GSC* relative to the model exists at high galactic latitudes; a significant deficit of faint stars in the *GSC* is present at the prime meridian; a surplus of faint stars in the *GSC* can be seen at most of the other areas. Several explanations for the trends were suggested in (Malkov & Smirnov 1994). However, we have found that the *GSC* does not easily lend itself to statistical studies, due to various irregularities in the stellar classifications. Therefore, we have had to design methods of reclassifying *GSC* data, using both statistical and artificial intelligence methods.

6. Modelling of the Quasi-Empirical Mass-Luminosity and Mass-Radius Relations for the Region of Low and Intermediate Mass Stars

The mass-luminosity relation (MLR) plays a prominent role in many astrophysical fields. First of all it helps to estimate stellar mass - an all-important stellar parameter, mostly only indirectly known from observations. The MLR is also especially valuable for transformation of the observed luminosity function to the initial mass function, which is of key importance in star-formation and galactic-evolution studies. As the transformation involves the MLR derivative, knowledge of the precise shape of the MLR is highly desirable. The MLR fine structure in the domains of low-mass ($0.08m_\odot - 0.8m_\odot$) and of intermediate-mass stars ($0.8m_\odot - 6m_\odot$) is a subject of a constant interest to investigators at the present time for several reasons.

The number of accurate observational data (masses, luminosities, photometry etc.) rapidly increases for moderate-mass stars. The detached double-lined eclipsing binaries give us a set of most accurate, fundamental determinations of physical parameters of the stars (mass, radius, effective temperatures, luminosity, etc.). Present typical accuracy for this kind of star enables us to hope for deeper astrophysical insight then merely "improving" "mean" relations. But when uncertainties in masses become less then 5%, the deviations of the individual systems from a mean relation are due not to observational errors, but to real differences in evolution and composition. That is why averaging any number of accurate binary masses and luminosities will not improve one-dimensional calibrations decisively.

We constructed a set of the main-sequence double-line detached eclipsing binaries by selection from the *Catalogue of Astrophysical Parameters of Binary Systems* (Malkov, 1993). As only three eclipsing systems have low-mass components, we completed the investigated set in the low-mass domain with high-quality data for dynamical masses and luminosities of the components of visual and spectroscopic low-mass binaries. Thus, the final set contains data for 43 intermediate-mass eclipsing binaries, three low-mass eclipsing binaries and 22 low-mass double and triple visual and spectroscopic systems (48 components). Data for masses, radii, effective temperatures and luminosities of the eclipsing binaries were selected from the the *Catalogue of Astrophysical Parameters*; the set of low-mass systems was mainly extracted from the *Catalogue of Nearby Stars* (Gliese & Jahreiss 1991). Dynamical masses for these systems were se-

https://doi.org/10.1017/S0251107X00000961 Published online by Cambridge University Press

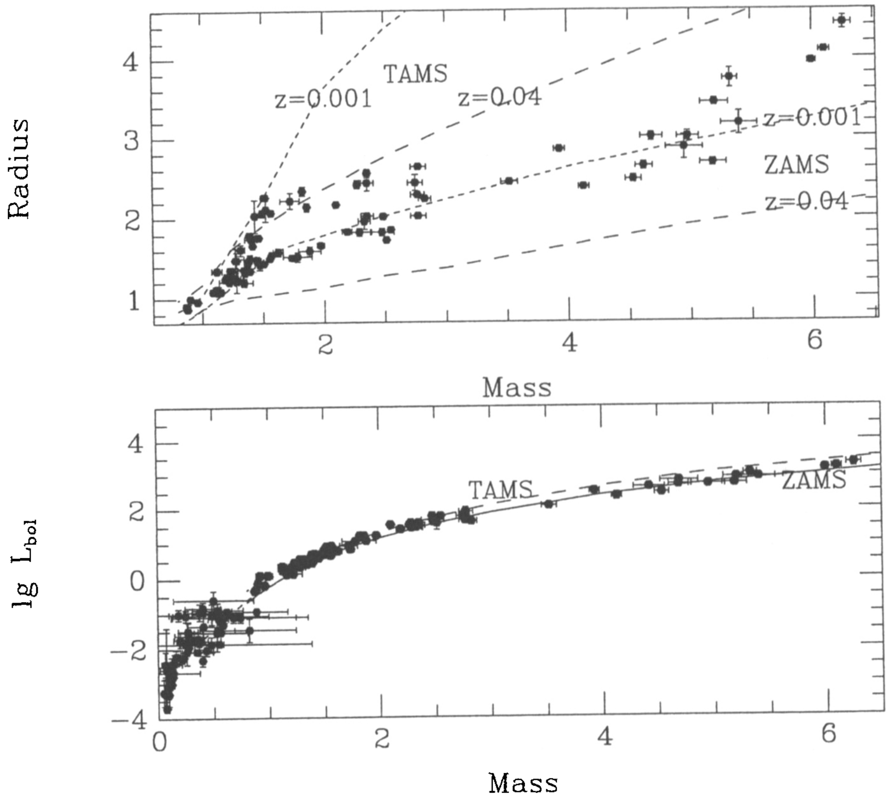

Figure 4. The observational data are presented in the mass-radius and mass-luminosity planes. The data for components of eclipsing binaries (all stars with $m > 0.8m_{\odot}$) are selected from Malkov's (1993) catalogue; the data for the low-nmass stars are mainly extracted from the original publications, the parallaxes needed for calculation of the bolometric luminosities from the photometry, and for verification of the mass data, were taken from the catalogues of van Altena et al. (1991) and *HIPPARCOS Output Catalogue (ESA 1997)*. ZAMS and TAMS lines shown in the mass-luminosity plane have been calculated for solar abundance, according to the grids of stellar models published by the Geneva group (Schaller et al. 1992, Shaerer et al. 1993a,b, Charbonnel et al. 1993, 1996 and 1999, Meynet et al. 1994, Mowlavi et al. 1998); ZAMS for the low-mass stars is from Baraffe et al. (1998). In the mass-radius plane both ZAMS and TAMS are shown for two limiting abundances for Population I stars. It can easily be seen that the scatter of the observational data (especially in the mass-radius plane) is much greater than the estimated observational errors.

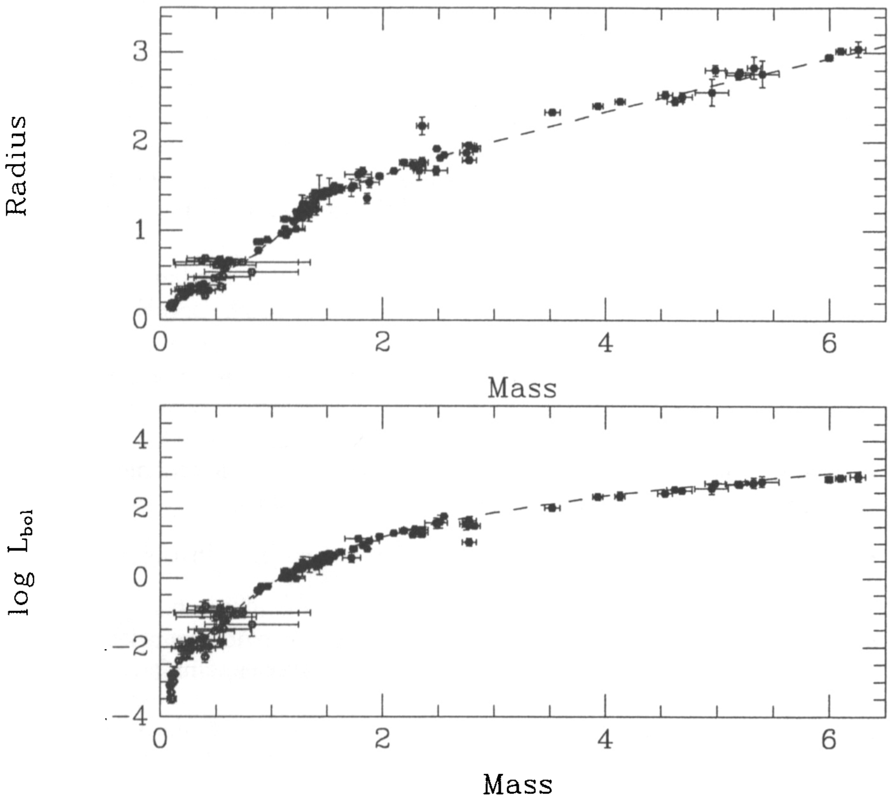

Figure 5. The same set of stars with the data for radii and luminosities "corrected" for the effects of evolution and abundance variations. The scatter shown around the plotted solar-abundance ZAMS lines is caused mainly by observational error.

https://doi.org/10.1017/S0251107X00000961 Published online by Cambridge University Press

lected from the original publications, as well as the multicolor photometry. The parallaxes necessary for calculation of the bolometric luminosities from the photometry and for verification of the mass data were taken from the catalogues of van Altena et al. (1991) and *HIPPARCOS Output Catalogue (ESA 1997)*. The data are presented in Figure 5.

We tried to reveal existence of fine structure of the MLR by looking for systematic differences between the present models and modern data on luminosities and dynamical masses of MS stars of spectra from late B to M. To remove the influence of the effects of evolution within the main sequence and of the chemical-composition dispersion, we calculated for the investigated set of stars most probable ages and metallicities derived from recent stellar models using constraints arising from the common origin of components (see Figure 5). Analysis of the empirical MLR, considering the influence of these effects, shows in general perfect agreement of observations with present-day models. We also note an existence of systematic deviations of theoretical MLR between $1m_{\odot}$ and $3m_{\odot}$.

7. Conclusions

One can see that astronomical catalogues (and, more generally, astronomical data sources) are good examples of how

- modern data can be made operatively available to astronomers in developing countries by means of standard Internet tools;
- modern theoretical studies can be carried out without involving large telescopes;
- statistical properties of astronomical objects provide us with the most common parameters of their families: stars, galaxies, clusters, planets.

Acknowledgments. OM thanks the SOC of the conference for financial support that made this presentation possible. OM and DK also asknowledge the Russian Academy of Sciences for the aid provided in the frame of the "Young Scientists Support Program".

References

Bahcall, J.N. & Soneira, R.M. 1980, ApJS, 44, 73

Baraffe, I., Chabrier, G., Allard, F., & Hautschildt, P. H. A&A, 337, 403, 1998

Batten, A.H., Fletcher, J.M., & McCarthy, D.G. 1989 Publ. Dominion Astrophys. Obs. 17

Charbonnel, C., Dappen, W., Shaerer, G., Bernasoni, P. A., Meader A., Meynet, G., & Mowlavi, N., 1999, A&AS, 135, 405

Charbonnel, C., Meynet, G., Meader, A., & Shaerer, G. 1996, A&AS, 115, 339

Charbonnel, C., Meynet, G., Meader, A., Shaller, D., & Shaerer, G. 1993, A&AS, 101, 415

ESA 1997, *The HIPPARCHOS and Tycho Catalogues*, ESA SP-1200

Gliese, W. & Jahreiss, H. 1991, *Nearby Stars*, Preliminary 3rd Version, Astron. Rechen-Institut, Heidelberg

Jeffers, H.M., van den Bos, W.H., & Greeby F.M. 1963, Lick Obs. Publ. 21.

Jenkner, H., Lasker, B. M., Sturch, C.R., McLean, B.J., Shara, M. M. and Russell, J. L., 1990, AJ, 99, 2081

Kraicheva, Z., Popova, E., Tutukov, A., & Yungelson, L. 1980 Bull. Inform. CDS 19, 71

Lasker, B.M., Sturch, C.S., McLean, B.J., Russell, J.L., Jenkner, H., and Shara, M.M. 1990, AJ, 99, 1019

Malkov, O.Yu. 1993, Bull. Inf. CDS, 42, 27

Malkov, O.Yu. & Smirnov, O.M. 1994, in ASP Conf. Ser. Vol. 61, Astronomical Data Analysis Software and Systems III, ed. D.R. Crabtree, R.J. Hanisch, & J. Barnes (San Francisco: ASP), 187

Malkov, O.Yu. & Smirnov, O.M. 1995, in ASP Conf. Ser. Vol. 77, Astronomical Data Analysis Software and Systems IV, ed. R.A. Shaw, H.E. Payne, & J.J.E.Hayes (San Francisco: ASP), 182

Malkov, O.Yu. & Smirnov, O.M. 1999, in ASP Conf. Ser. Vol. 172, *Astronomical Data Analysis Software and Systems VIII*, ed. D.M. Mehringer, R.L. Plante, & D.A. Roberts (San Francisco: ASP), 407

Meynet, G., Meader, A., Shaller, D., Shaerer, G., & Charbonnel, C. 1994, A&AS, 103, 97

Monet, D. 1996, USNO-A: *A Catalog of Astrometric Standards*, (Washington: USNO)

Mowlavi, N., Shaerer, G., Meynet, G., Bernasconi, P. A., Charbonnel, C., & Meader, A. 1998, A&AS, 128, 471

Pasian, F., Marcucci, P., Pucillo, M., Vuerli, C., Malkov, O.Yu., Smirnov, O.M., Monai, S., Conconi, P., & Molinari, E. 1998, in ASP Conf. Ser., Vol. 145, *Astronomical Data Analysis Software and Systems VII*, ed. R. Albrecht, R.N. Hook, & H.A. Bushouse (San Francisco: ASP), 433

Roeser, S. & Bastian, U. 1988, A&AS, 74, 449

Roeser, S. & Bastian, U. 1993, Bull. Inform. CDS, 42, 11

Roeser, S., Bastian, U., & Kuzmin, A. 1993, A&AS, 105, 301

Russell, J.L., Lasker, B.L., McLean, B.J., Sturch, C.R., and Jenkner, H. 1990, AJ, 99, 2059

Shaller, D., Shaerer, G., Meynet, G., & Meader, A. 1992, A&AS, 96, 269

Shaerer, G., Meynet, G., Meader, A., & Shaller, D. 1993a, A&AS, 98, 523

Shaerer, G., Charbonnel, C., Meynet, G., Meader, A., & Shaller, D. 1993b, A&AS, 102, 339

Smirnov, O.M. & Malkov, O.Yu. 1997, in ASP Conf. Ser. Vol. 125, *Astronomical Data Analysis Software and Systems VIII*, ed. G. Hunt & H.E. Payne (San Francisco: ASP), 426

Smirnov, O.M. & Malkov, O.Yu. 1999, in ASP Conf. Ser. Vol. 172, *Astronomical Data Analysis Software and Systems VIII*, ed. D.M. Mehringer, R.L. Plante, & D.A. Roberts (San Francisco: ASP), 442

van Altena, W.F., Lee, J.T., & Hoffleit, D., 1991, *The General Catalogue of Trigonometric Stellar Parallaxes*, Preliminary Version, Yale University Observatory

Worley, C.E. & Heintz, W.D. 1983, Publ. U.S. Naval Obs. (2) 24, part VII

Worley, C.E. & Douglass, G.G. 1996, US Naval Observatory (unpublished).

Discussion

Chamcham asked if the data of all the catalogues had been reduced. Malkov replied that some had been. In deriving the mass-luminosity relations, they reduced the observed luminosities of the stars "removing" the changes caused by evolutionary effects (thus obtaining the ZAMS relation) and they reduced the differences arising from abundance variations, obtaining the relation for solar chemical composition. Fierro asked how many students in the Moscow Centre for Astronomical Data used these catalogues in their work. Malkov believed that they all did.

https://doi.org/10.1017/S0251107X00000961 Published online by Cambridge University Press