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COMMENTS ON "*BVRI*-PHOTOMETRY OF THE BRIGHTEST STARS IN THE MAGELLANIC CLOUDS" BY MENDOZA (1970)

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RESUMEN

En este trabajo presento una revisión del artículo "*BVRI*-Photometry of the Brightest Stars in the Magellanic Clouds" por E. E. Mendoza V., 1970, BOTT, 5, 35, 269. Describo las condiciones en las cuales se desarrollaron las ideas del artículo, las técnicas usadas y los resultados obtenidos. Es de señalar que Mendoza fue uno de los primeros en sugerir que las Nubes de Magallanes tienen bajo contenido en metales. Finalmente presento una breve comparación con los estudios modernos en el campo.

ABSTRACT

In this paper I present a review of the article "*BVRI*-Photometry of the Brightest Stars in the Magellanic Clouds" by E. E. Mendoza V., 1970, BOTT, 5, 35, 269. I describe the background on which the ideas of the paper were developed, the techniques used and the obtained results. It is worth noting that Mendoza was one of the first to suggest the lower metal content of the Magellanic Clouds. Finally I present a brief comparison with the modern studies in the field.

Key Words: H II regions — ISM: jets and outflows — stars: mass-loss — stars: pre-main sequence

1. INTRODUCTION

One of the tasks of contemporary astrophysics is the construction of a reasonable theory of stellar evolution. The process involves two steps. It requires firstly, a system of equations describing the physical processes in the star and how it emits is constructed. Based on that theory, a set of data are calculated and presented in such a form that they can be easily compared to the observations. Secondly, observations are performed and the comparison between them and the theoretical predictions is used to acquire information of the evolutionary status of the star. On the other hand, if the observations and the predictions are too different, the theory is adjusted. So the stellar evolution theory is used to interpret the observations, and the observations are used to adjust the theory. The main tool for such comparison has been, and is, the Hertzsprung-Russell (HR) diagram. Unfortunately, it relates the luminosity of a star to its temperature. Both quantities are not directly observable. It requires time to obtain temperature and luminosity of a single star from the analysis of its spectrum and it is impractical to use this method of statistically signifficant studies for large groups of stars.

One possible solution to the problem of analysis of large groups of objects is to observe them only in a few spectral bands. The bands should not be too wide, so the spectral energy distribution can be reconstructed, but not too narrow so the detector can obtain reasonable S/N ratios even for weak objects. This idea was used with photographic plates as detectors. But the low signal-to-noise ratio of the plates and the non-linear response limited their use.

One important change in the observational astronomy was made by the introduction of the photomultiplier as a detector. The photomultipliers were invented between the two World Wars but it seems that they were not used for astronomical applications until the late forties of the XX century. In 1950–1951 Johnson & Morgan (1953) began the work on establishing a photometric system in three pass bands. This was a compromise between the minimal number of pass bands (colors) and the spectral response of the photomultiplier tube. The result was the UBV photometric system. The color-magnitude, $(V, B-V)$ diagram is equivalent of the brightness-temperature HR diagram and the $(U-B, B-V)$ color-color diagram allows the determination of interstellar reddening.

The UBV system provided a useful tool for the stellar astrophysicists, but soon it was realized that the determination of precise spectral energy distribution of stars needs more spectral bands. The development of detectors sensitive to the red and infrared part of the spectrum stimulated the development of an additional two filter system redward of

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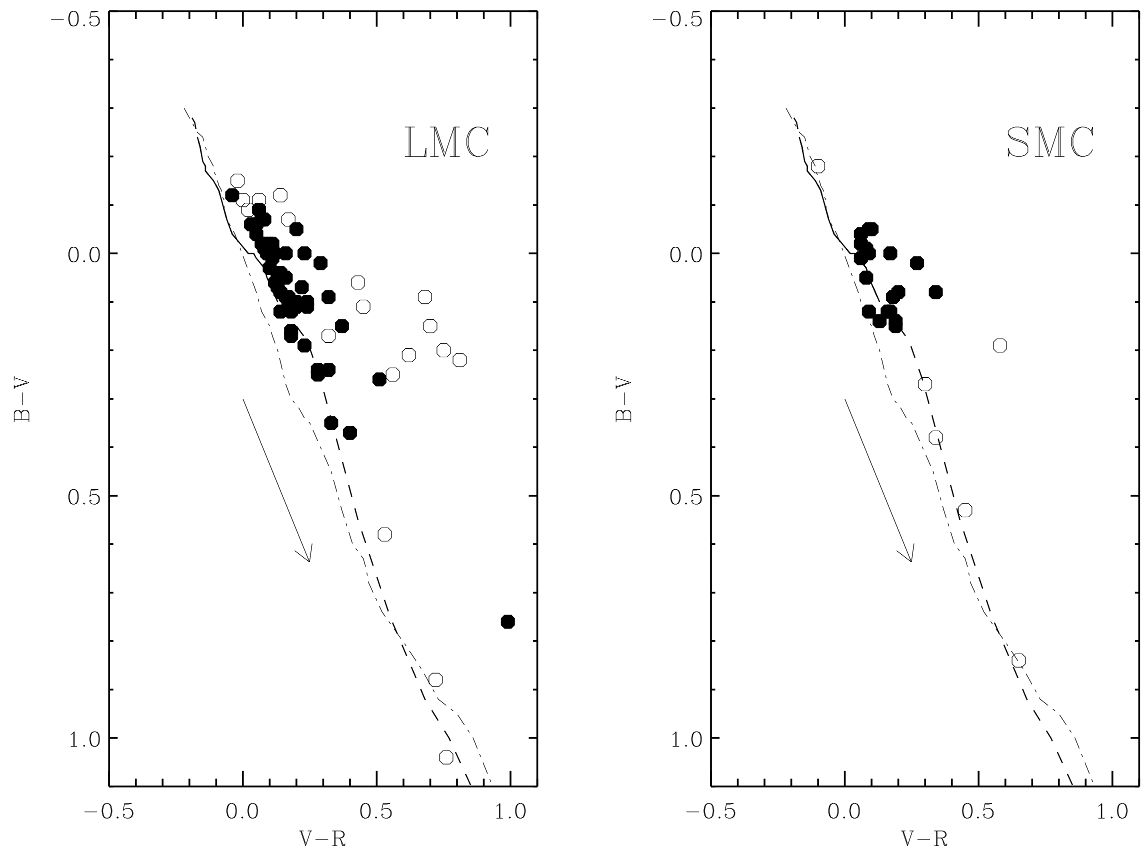

Fig. 1. Two color diagram of the LMC (left) and SMC (right) stars. The filled circles mark the stars with spectral classes B0-A5. The line represents the intrinsic colors relation for galactic supergiants (Ducati et al. 2001). The solid part of the intrinsic colors line corresponds to the spectral classes B0-A5. The thin dash-dotted line is the intrinsic color relation for main sequence stars. The arrow indicates the reddening vector for A_V=1.0 and R=3.1. Note that most objects lie above the galactic intrinsic colors line and not in the direction of the reddening.

UBV. Kron & Smith (1951) introduced the R and I magnitudes and $R - I$ color which were further developed by Kron et al. (1957). Johnson (1962) introduced an extension of the system to the red with J, H, and K filters. Finally Johnson (1964) summarized the complete 10 filter *UBVRIJHKLM* system with the appropriate set of standard stars and zero point definitions. As part of the same process, a *UBVRI* photometer was constructed in Tonantzintla, Mexico (Mendoza 1963) and was used to extend the set of standard stars (Johnson 1964) for studies of several stellar clusters.

Thus, in the beginning of the sixties the photometric system was established and its applications for stellar studies were increasing in numbers. The standard relation between colors and magnitudes for stars in the Galaxy were established. The next step was the comparison between stars born in different environments. At that time the only objects feasible for such observations were the brightest stars of the Magellanic Clouds.

2. EUGENIO MENDOZA'S "*BVRI*-PHOTOMETRY OF THE BRIGHTEST STARS IN THE MAGELLANIC CLOUDS"

Following Johnson example, a photometer was built in Tonantzintla and used as part of the program for establishing the standard stars for *UBVRI* system as defined by Johnson (1964). The system was used for photometric studies of several open clusters and associations (Mendoza 1963, 1967a,b). The logical extension of the project was to observe stars in other galaxies and compare their photometric properties to the galactic stars. The observations were performed at the 36 and 60 inch telescopes of Cerro Tololo Inter-American Observatory using the same set of filters and photomultipliers as in Tonantzintla system. Observations of 100 stars (75 in the LMC and 25 in the SMC) were obtained and reduced in the standard form. The data were presented in the paper.

As stated in the introduction, the goal of the paper is to compare the photometric properties of the stars in the Milky Way and the Clouds. Mendoza used the data for χ and h Per from his previous study (Mendoza 1967b) in order to establish the intrinsic colors for the supergiant stars in B0-A5 spectral classes. Once that was done, the $B-V$, $V-R$ and $R-I$ colors of the stars of LMC and SMC were compared to the determined intrinsic colors. I reproduce the $(B-V, V-R)$ figures using the data from Mendoza's (1970) paper together with the intrinsic colors for galactic supergiants as determined by Ducati et al. (2001; Figure 1). The figure shows that most of the objects lie above the line defined by the galactic stars. This difference cannot be the result of reddening. On Figure 1 the stars with spectral classes B0-A5 are marked. The intrinsic colors of these spectral classes are also marked. The reddening vector as defined by Cardelli et al. (1989) points almost parallel to the intrinsic colors line. Therefore if the reddening is not very peculiar, the observed difference cannot be result of the reddening. The same result is obtained for the $(R-I, V-R)$ diagram.

The two color diagrams allow the determination of the reddening. There are two possible ways to do that. One is to use the standard slope of the reddening line and calculate the color excess along it. On the other hand, if the spectral classes of the stars are available, one can calculate the reddening as the difference between the observed color and the one on the intrinsic colors line. Then the ratio of the color excesses in different bands can give information on the reddening law. Mendoza determined $E(B-V)$, $E(V-R)$ and $E(R-I)$ using his intrinsic colors and the spectral classification of Feast et al. (1960). In Figure 2 Mendoza's result is reproduced but plotting the expected value of $E(R-I)/E(V-R)$ from Cardelli et al (1989). Contrary to the galactic stars, observed color excesses of the objects have a much larger scatter. Again, the conclusion is that the scatter is too large to be simply explained with bad determination of the excesses but rather it points to a real difference between the Galaxy and the Clouds.

Finally, using the color excesses and the spectral classes, Mendoza constructed the HR diagram for the two galaxies. The diagrams show a big scatter but comparing them Mendoza determined that the distance modulus to the LMC is $m-M > 18.0$ mag and the difference of the distance moduli of the two clouds is 0.25 mag. Both values are good estimates to the modern determination of $(m-M)_{\rm LMC} = 18.50$

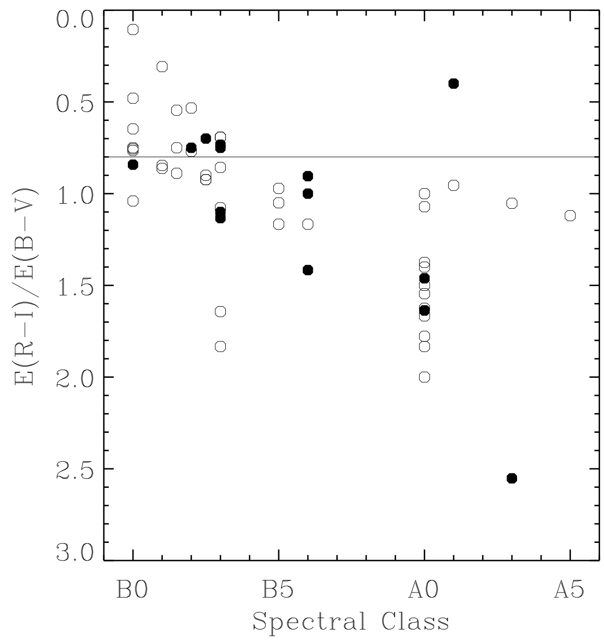

Fig. 2. Ratio between $E(B-V)$ and $E(R-I)$ for the stars in LMC (open circles) and SMC (filled circles). Only stars with spectral classes between B0 and A5 are shown. Stars with peculiar spectra are omitted. The horizontal line represents the value expected form Cardelli et al. (1989) for R=3.1

(Pietrzyński et al. 2009) and $(m-M)_{\rm SMC} - (m-M)_{\rm LMC} = 0.35$ (Ciechanowska et al. 2010).

3. THE RESULTS DERIVED AND THEIR IMPACT

The photometry of the stars in the Magellanic clouds gives two interesting results. In Figure 1 the relations between the intrinsic colors of the supergiants and the main sequence stars is shown. It is seen (Figure 1), that the supergiants lie above the main sequence stars. The LMC and SMC stars lie even further above. Therefore, Mendoza concluded that the stars in the Clouds must be super luminous relative to their galactic equivalents.

The difference between the galactic intrinsic colors and reddening shown on the color-color diagrams (Figure 1) and the color excess-spectral type diagrams (Figure 2) can be interpreted in several different ways. It seems that the diagrams points to redder $V-R$ colors for the LMC/SMC objects than the galactic stars. Mendoza gives a list of possible interpretations. It cannot be explained either by differences in the extinction law or peculiar background radiation or by red companions because the scatter seems independent of the position on the sky. The selection of stars with B0-A5 spectral classes without any peculiarities rules out the incorrect intrinsic colors or peculiar spectral energy distributions. Thus, Mendoza arrived at the conclusion that the red excess could be due to circumstellar dust clouds or due to difference in the chemical composition of the stars in the Magellanic clouds. Peimbert & Spinrad (1970) had shown that the helium abundance in Magellanic clouds is similar to that of the Milky Way. Based on that, Mendoza concluded that the difference between the colors and therefore the spectral energy distributions of the stars in the Galaxy and Magellanic Clouds is due to lower metal composition of the stars in the Clouds.

It is worth noting that at the time of the publication of Mendoza's paper there was no clear idea on the chemical composition of the other galaxies. There is only one determination of the chemical abundances of stars in the Clouds (Przybylski 1965). The author claims that this is the first such study. In this sense, Mendoza's result is one of the first suggestions on the low metallicity of the stars in the Magellanic clouds.

Johnson photometric system is one of the most popular in contemporary astronomy. The techniques established in the sixties and seventies are almost unchanged. The new photometric programs use the same system of standard stars and in most of the cases the conversion from one system to another is relatively easy. In that sense the magnitude and color database published by Mendoza is a treasure box for many studies of long period variables and other peculiar objects.

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