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"PHOTOELECTRIC PHOTOMETRY OF CEPHEIDS" BY MITCHELL ET AL. (1964): AN OVERVIEW OF ITS ASTROPHYSICAL RELEVANCE

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RESUMEN

El artículo de R. I. Mitchell, B. Iriarte, D. Steinmetz y H. L. Johnson, 1964, BOTT, 3, 24, 153 es uno de los más citados del BOTT. En este se resalta cómo este trabajo ha influido en estudios subsecuentes de estrellas Cefeidas y otros campos de la astronomía estelar. Se presenta un breve recuento de la utilidad de los colores de estrellas Cefeidas en la determinación de algunos de sus parámetros físicos de mayor relevancia para la astrofísica estelar y la escala de distancias.

ABSTRACT

The paper by R. I. Mitchell, B. Iriarte, D. Steinmetz and H. L. Johnson, 1964, BOTT, 3, 24, 153 is among the most cited papers published in the BOTT. In this review it is highlighted how this work has impacted subsequent work on Cepheid stars and other fields of galactic astronomy. An overview of the relevance of Cepheid colors in the determination of physical quantities of astrophysical interest is given.

Key Words: stars: variables: Cepheids — techniques: photometric

1. INTRODUCTION

Cepheid stars have been long undisputed standard candles as cosmic distance indicators. Their Period-Luminosity relationship has been recognized as the corner stone of the distance scale in the Universe (Sandage 1999). Cepheids are important in three obvious astronomical objectives; stellar astrophysics, Galactic structure and extragalactic research. During the last 25 years the major improvements in the calibration of the P-L relation rest on the employment of near infrared measurements as the reddening effects are reduced (e.g., Feast 1994), and the use of the Hubble Space Telescope to measure distant Cepheids in the Virgo Cluster (Freedman et al. 1994). For thorough discussions on the the calibration of the P-L relation the reader is refered to the papers by Feast & Catchpole (1997), Sandage et al. (1999) and Gautschy (2000). There is no doubt that the results on the Cepheid distance scale are sustained on accurate and homogeneous data bases. However, 45 years ago such data bases were being built up. The paper by Mitchell et al. (1964, hereafter MISJ-paper) that we are commenting on in this note is probably the first homogeneous catalogue of UBV photometry for a large sample of Cepheids, and therefore its contribution to later work has been substantial.

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2. THE MISJ-PAPER: WHAT IT CONTAINS?

The catalogue contains about 10000 individual UBV observations and light curves for 300 Cepheids. Not all these observations are original in this paper, given that about 8000 were collected from the literature (Eggen, 1951; Eggen, Gascoigne, & Burr 1957; Walraven, Muller, & Oosterhoff 1958; Abt & Hardie 1960; Oosterhoff 1960; Weaver, Steinmetz, & Mitchell 1961; Irwin 1961; Bahner, Hiltner, & Kraft 1962). A great achievement of the paper is the transformation of these bulky scattered collection of photometric data into a homogeneous useful data set in the Johnson UBV system. Such transformations were calculated using Cepheid stars in common with all the published lists in different photometric systems. On the other hand, about 2000 observations are original and were carried out mostly by Dr. Sotirios N. Svolopoulos. The main goal of the paper was to provide a large homogeneous collection of data on Cepheids such that can be employed in studies of Galactic rotation.

3. HOW MISJ-PAPER CONTRIBUTED TO SUBSECUENT WORK

The MISJ-paper has been mostly cited in subsecuent literature as a source of data to estimate times of maximum light, which in turn contribute to the secular period changes determinations of selected Cepheids. Secular period changes are the result of the stellar evolution across the instability strip and it is perhaps the only evidence of stellar evolution that can be observed and measured empirically during a astronomer's life time.

Examples of studies of period variations in classical Cepheids that have made use of the data in the MISJ-paper would be too large to be cited here as can be confirmed from a visit to the ADS. The two most recent citations are connected with the evolutionary changes in RS Pup (Berdnikov et al. 2009) and RT Aur (Turner et al. 2007).

Not only the long term period changes can be discussed from accurate time photometric series but also the amplitude variations. Amplitude modulations can be the result structural changes in binary systems or evolutionary changes as the star leaves the instability strip. Clear amplitude variations have been documented for Polaris (Arellano Ferro 1983) and more recently for Y Oph (Pop et al. 2010).

The relevance of photometric colors of Cepheids in estimating effective temperatures can be seen in the work of Sanwal & Rautela (1998) and have also been used to calculate first approach temperatures for spectroscopic work (Giridhar 1983). The MISJ-paper data was useful to compare theoretical predictions of light curve shapes for type II BL Her stars which in turn lead to estimations of stellar masses (Carson & Stothers 1982; King, Cox, & Hodson 1981).

While it is well known that the stellar photometric colors can be used to estimate the stellar radius by means of the Baade-Wesselink method, the MISJ-paper data have been used to discussed systematic differences produced by the different colors (Boehm-Vitense et al. 1989) and to calculate radii for particular stars (e.g., Turner 1988 for δ Cepheid; Imbert 1983 for AD Gem).

Selected Cepheids and their UBV photometry in the MISJ-paper have also been used for the kinematical analysis of Cepheids to determine the solar motion, galactocentric distance and the Oort's constants (Takase 1970).

4. SUBSECUENT PHOTOMETRIC CATALOGUES

During the decades since 1964 a few other large and homogeneous photometric catalogues of types I and II Cepheids have been published; noticeable by Moffett & Barnes (1984) in the $BVRI$ system, Berdnikov & Patsukhova (1994) in BV, Laney & Stobie (1992) in $JHKL$, the compliation by Fernie et al. (1995) in BV, Schmidt et al. (2004, 2005a,b) in $UBVRI$. In the Strömgren $uvby-\beta$ system there are the catalogues of Feltz & McNamara (1980), Eggen (1983, 1985), Meakes et al. (1991) and Arellano Ferro et al. (1998). The above photometric catalogues have been very useful in different fronts of stellar astrophysics and no doubt will continue to be a valuable well of information to confront problems of present interest. In § 5 it is given an overview of several aspects of astrophysical interest where the colors of Cepheids have made their contribution, such as the determination of stellar physical parameters of structural and evolutionary relevance and functional calibrations related to the cosmic distance scale.

5. USEFULNESS OF CEPHEIDS PHOTOMETRIC DATA

It is difficult to imagine a problem related to Cepheid stars that does not requiere of some photometric colors. As Cepheids play a prominent role in several aspects of stellar structure and evolution and as Galactic and extragalactic distance indicactors, their photometric values and variations will continue being highly valuable data. And as new techinques and instruments provide more accurate data, it is likely that new photometric compilations of Cepheids will continue to make their appearance in the future.

5.1. *Distance indicators and reddening*

The most prominent and relevant property of Cepheids is, beyond any doubt, their Period-Luminosity (P-L) and Period-Luminosity-Color (P-L-C) relationships since they can be used to calculate cosmic distances. For a recent calibration of the slope and zero point of the P-L relationship the reader is refered to the paper by Fouqué et al. (2003). These P-L and P-L-C relationships are useful tools if one can estimate the effects of interstelar extinction and reddening. Hence, determining the color excesses of Cepheids has been the major goal of much research in recent past (e.g., Canavaggia, Mianes, & Rousseau 1975; Pel 1978; Feltz & McNamara 1980). The largest body of Cepheid reddenings reduced to a homogeneous system can be found in the work of Fernie (1994) who calculated values of $E(B-V)$ from BV data and a functional relationship that includes the $B-V$ color at maximum light, the amplitude in V and the period, for about 500 Cepheids. A more recent attempt to homogenize the color excess scale for 323 Cepheids using different photometric systems was made by Kim & Yushchenko (2005). From the Strömgren system a calibration and values of $E(b-y)$ for 116 Cepheids are given by Chulhee (2008).

5.2. *Color-Temperature relationship*

As the Cepheid temperature calibration plays a major part in calculating evolutionary and pulsation masses, and as tracing the instability strip, defining the Cepheid temperature scale is quite relevant. Photometric color-temperature relations are also useful in radii determinations via the Baade-Wesselink method (see § 5.3) and for abundance analysis of Galactic and extragalactic Cepheids. Among the first attempts to measure effective temperatures in individual Cepheids from their energy distributions there are those by Oke (1961a,b) using photoelectric spectrum-scans. Further efforts to define the temperature scale of Cepheids by a similar technique but using upgraded stellar models were carried out Teays (1986) and Teays & Schmidt (1987).

A color-temperature calibration for 13 Cepheids in open clusters using the $B-V$ and $V-R$ colors was carried out by Fry & Carney (1999) whom, after applying small corrections due to differences in gravity, found the functional calibratios

$$\Theta_{\rm eff} = (0.716\pm0.015)+(0.225\pm0.017)(B-V)_{\rm o}, \quad (1)$$

$$\Theta_{\rm eff} = (0.609\pm0.024)+(0.429\pm0.034)(V-R)_{\rm o}, \quad (2)$$

where $\Theta_{\rm eff} = 5040K/T_{\rm eff}$.

5.3. *Cepheids Radii*

Photometric colors of Cepheids also play a key role in the determination of mean radii and radius variations along the pulsation cycle.

To extract the variation in stellar radius from the light curve of a Cepheid, it is needed to select an appropriate color index to infer the temperature such that the radius and the distance can be estimated.

The Surface-Brightness method (Barnes & Evans 1976), or Barnes-Evans method as it is often called, (which is a variant of the Baade-Wesselink method), it is a geometric approach that leads to the mean radius and distance of a radially pulsating star. The angular diameter and radius of the star are related by

$$R_m + \Delta R = \frac{\phi d}{2000}, \quad (3)$$

where R_m and ΔR are the mean stellar radius and linear displacement of the stellar surface measured in solar radii, d is the distance in parsecs and ϕ the angular diameter in milliseconds of arc. ΔR can be obtained as a function of the pulsation phase by integration of the radial velocity curve (see Arellano Ferro & Rosenzweig 2000 for a discussion). Figure 1 shows the parallel variation of the angular diameter ϕ and the surface displacement ΔR and hence their linear relation for the star TT Aql.

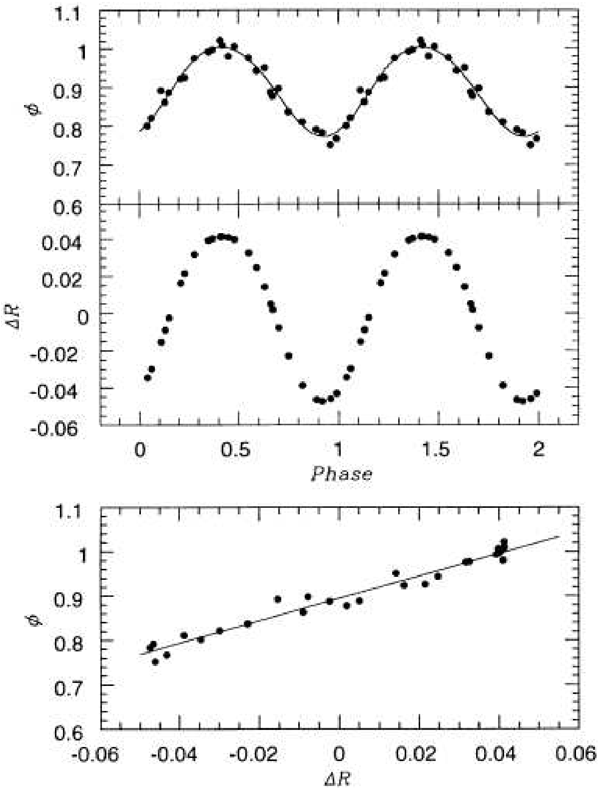

Fig. 1. Angular diameter (ϕ) and surface displacement (ΔR) variations and their linear relation for the star TT Aql. Figure taken from Arellano Ferro & Rosenzweig (2000).

The surface-brightness F_ν is defined as:

$$F_\nu = \log T_{\rm eff} + 0.1BC = 4.2207 - 0.1V_{\rm o} - 0.5\log\phi. \quad (4)$$

Since both $T_{\rm eff}$ and the bolometric correction BC can be correlated with the stellar color, F_ν can be obtained from a photometric color provided an appropriate calibration of equation 4. There exist several calibrations of equation 4 for several color indices; e.g., Barnes & Evans (1976) for $BVRI$ colors; Fouqué & Gieren (1997) for BRK and Laney & Stobie (1995) for $VRJK$ colors. An application of this approach to the Cepheids in the LMC is presented by Storm et al. (2000).

It is generally accepted that the use of near IR colors are convenient since they are less affected by interstellar reddening. However, as discussed by Fry & Carney (1999), in selecting the color to be used, the Surface-Brightness method requires that the distance between the line-forming layers, from which the radial velocities are obtained, and the continuum-forming layers, from which colors, temperatures, apparent luminosities, and apparent an-

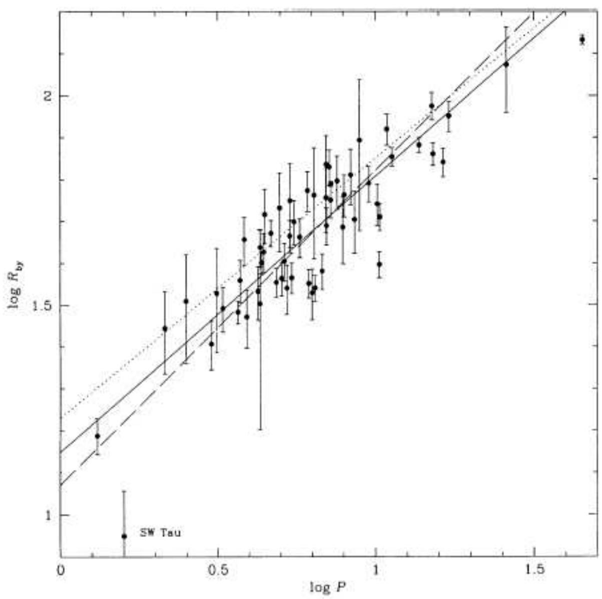

Fig. 2. Period-Radius relation for Cepheids defined by the intermediate band photometry approach (solid line). The calibrations of Laney & Stobie (1995) and Sachkov et al. (1998) are also shown (segmented and dotted lines respectively). Figure taken from Arellano Ferro & Rosenzweig (2000).

gular diameters are obtained, must be small and constant throughout the pulsational cycle. And also the distances of the continuum forming layers at the wavelengths of the filters should be zero or small and constant to prevent systematic errors. These authors conclude that the best broad band filter colour would be $B - V$. It can be argued that narrower band filters, such as the Strömgren *uvby*, would better fulfill the above conditions. A calibration of equation 4 for $(b - y)_{\rm o}$ and the radii and distances for a sample of 59 Galactic Cepheids have been offered by Arellano Ferro & Rosenzweig (2000).

The period-radius relationship obtained by Arellano Ferro & Rosenzweig (2000) is $\log R = 1.148(\pm 0.042) + 0.659(\pm 0.051) \log P$ and it is shown in Figure 2.

5.4. *Galactic kinematics of Cepheids*

Photometric color of Cepheids are also useful in studies of Galactic kinematics. A kinematic study of Cepheids fundamentally requires radial velocities, and distances. The role of colors and magnitudes in the estimation of distances through the P-L relation and the interstellar extinction corrections has been discussed in previous sections. A neat example of a approach to the kinematics of Cepheids can be found in the work of Takase (1970) who used the photometric and radial velocity compliation of Fernie & Hube (1968) and to some extent the photometry in the MISJ-paper and that of Takase (1969) to calculate among other things the solar motion components and its galactocentric distance and the Oort's constants A and B.

5.5. *Conclusions*

The contents and impact on subsequent work of MISJ-paper have been reviewed. The importance of time series photometric measurements of magnitudes and colors in Cepheid stars has been highlighted and their role in the determinations of physical parameters of astrophysical relevance has been overviewed. It is clear that magnitudes and colors of Cepheids are fundamental to the developement of our understanding of stellar astrophysics, Galactic kinematics and the cosmic distance scale. It is easy to forecast that this type of data, either gathered with small or large telescopes, from the ground or from the space, will continue to imprint our future work and our knowledge of the Universe.

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