Stellar Photometry Using Old Photographic Plates

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Received June 21, 2004; revised September 13, 2004

Abstract The precision of various methods of stellar photometry on old photographic plates is investigated using the original plates or their digitized copies from the plate collection of the Maria Mitchell Observatory (MMO). It is shown, in particular, that the simple and fast method of eye photometry is comparable in precision to the traditional "objective" methods using a microphotometer to measure the plates or image analysis software to measure digital copies of small parts of the plates obtained with a CCD camera. All these methods provide photometric accuracy of ±0.1–0.2 magnitude on the MMO plates. It is demonstrated that the high-performance commercially available scanner AgfaScan T5000 used for plate digitization at the MMO produces images that can be measured to a considerably higher precision of ±0.05 magnitude, which is sufficient for most purposes of photographic stellar photometry. The results of this investigation may be of interest to those who use old plates for stellar photometry, as well as to those who look for an adequate, fast, and relatively inexpensive scanner to digitize their plate archive.

1. Introduction

Photometry of old photographic plates remains an important tool for studying variable stars. For about a hundred years, from the late 19th to the late 20th century, photography was the only method of "multi-channel" astrophotometry. A huge amount of valuable information, in particular, information on the light curves of an enormous number of variable stars, is stored on the old plates in astronomical archives. A standard Kodak 8×10-inch photographic plate contains 0.5×10^9 "pixels" (developable grains) of 10 micron size, whereas even a large, by today's standards, $4{,}048 \times 4{,}048$ CCD chip contains 30 times fewer. The Wide-Field Plate Database of the Bulgarian Academy of Science (http://www.skyarchive.org/about.html) contains data on more than 2×10^6 wide-field (> 1°) plates from more than 300 archives. The photographic plate archive of the Maria Mitchell Observatory (MMO) is relatively small, about 8,000 plates, but it is rich for three particular areas of the sky in Sagittarius, Scutum, and Cygnus. It is also the first astronomical plate archive to have been completely digitized using a high-performance commercially available scanner (Shaeffer 2003).

In this paper we will present a broad analysis of the precision of stellar photometry obtainable, by different methods, with the original and digitized MMO plates. We hope that this analysis will be of interest to the potential users of the digitized MMO plate copies, as well as to a broader audience of those who use or plan to use old plates from other archives for stellar photometry. Moreover, these results may be encouraging for those who contemplate digitization of their plate archives and are looking for a reasonable compromise between the good but very slow and expensive single-channel astronomical microdensitometers and much faster and cheaper commercially available scanners whose quality for astronomical photometry and astrometry is still poorly known. Our conclusions are summarized in Talbe 1.

2. The MMO photographic plate archive

This archive contains more than 8,000 plates obtained from 1913 to 1995 with the observatory's 7.5-inch fast Cooke/Clark refractor (Friel 1992). The 8 × 10-inch plates have a scale of 240 arcsec/mm and a field of view 13° × 16°. The collection is relatively small, but it is concentrated on a few regions of the sky, and for these regions it is rich. The Scutum Cloud, three partly-overlapping regions in Cygnus (centered at DF Cyg, CI Cyg, and EY Cyg), a field in Sagittarius (centered at λ Sgr), and the Coma Cluster region are the best represented regions. The catalog of the collection is online (http://www.aas.org/%7Epboyce/mma/plates.htm) and is downloadable in Excel format. It can also be found on the Wide-Field Database (WFDB) of the Bulgarian Academy of Science and at the Vizier section of the CDS.

In 2002, the MMO completed a 1.5-year project of digitization of its photographic plate collection (Barkume and Strelnitski 2001; Davis and Strelnitski 2003; Shaeffer 2003). The customized, commercially available scanner AgfaScan T5000 was used for the project. An overview scan with a resolution of 840 dpi and two slightly overlapped high-resolution (2,500 dpi) scans for the West and East halves of each plate were put on a CD. Copies of the CD's are available on request to vladimir@mmo.org.

3. Comparison of the traditional methods of plate photometry

The first, classical method of stellar photometry on photographic plates, and the dominant method through the first half of the 20th century, was simple eye photometry originated by Argelander for visual estimates and developed further by several distinguished observers of variable stars (Pickering, Neiland, Blazhko). A magnifying glass or a microscope is the only tool of the operator. The smallest distinguishable difference in photographic effects between two stars (mostly, the diameters of the star images) is defined by the observer as one "step." This provides a unit of scale for the "instrumental" measure of the difference in intensities of two stellar images, which can be used to estimate greater differences. Interpolation between two comparison stars of known brightness, encompassing the unknown brightness of the variable, increases the accuracy of the estimate.

By the middle of the century, "objective," photoelectric microphotometers were introduced as a means of measurements. An iris microphotometer was long considered to be the most accurate method of photographic stellar photometry. The MMO, like many other observatories with photographic plate archives, possesses a (Cuffey) iris photometer. Using a variable diaphragm, such a photometer allows for an accurate measurement of the intensity of a stellar image ("iris number"), which is determined mainly by the diameter of the image.

In the 1990's, astronomers started to experiment with using digital cameras to make digital copies of the target area on the plate and measure the magnitudes of the star images using computers with standard image reduction software. MMO possesses a dedicated CCD camera, Kodak DCS200, which allows for digitization of selected areas on the plates (Burkholder 1995).

Since all these traditional methods are still in use, we decided to undertake their comparative analysis and elaborate some recommendations for the observers. The preliminary results were reported by Strelnitski, Springob, and Tam (1999).

Thirteen stars in the open cluster M25, with the catalogued photoelectric *B* magnitudes (Sandage 1960; Johnson 1960) were measured on seven typical plates from the Maria Mitchell Observatory collection using each of the three methods. The catalogued magnitudes of the stars range from 9.0 to 14.5. With one exception, the intervals between the two stars of adjacent magnitudes do not surpass 1 magnitude and in most cases they are 0.2–0.3 magnitude. The measurements were the determination of the "instrumental" magnitude difference for each pair of stars of adjacent magnitudes. Two methods involving relatively high elements of subjectivity, eye photometry and microphotometry, were performed independently by two of the present authors (F. T. and C. S.).

The instrumental magnitude differences (i.e. the number of the observer's "steps" in the eye photometry, the difference of the "iris numbers" in the iris microphotometry, and the difference of the instrumental magnitudes in the IRAF photometry of the digitized image) were plotted against the catalogued magnitude differences, in order of increasing star magnitude, with an arbitrarily chosen zero point star. This dependence was approximated by a second order polynomial (a straight line, in the case of the eye photometry). The standard deviations of individual measurements from this best-fit curve (in the units of the standard, catalogued magnitudes) can be used as a measure of each method's accuracy. These standard deviations are presented in Table 2 (see Section 4 regarding the fourth column in this table).

4. Photometric quality of plate copies digitized with AgfaScan T5000

In order to estimate the adequacy of the digitized plate copies obtained with the AgfaScan T5000 for stellar photometry, we first undertook a preliminary study to see whether digitization with this scanner entails serious losses of photometric information (Barkume and Strelnitski 2001). The eye photometry of the same thirteen standard stars from M25, on the same seven plates, as described in Section 3, was repeated but, in this case, the instrumental magnitudes of the stars were estimated from the digital copies of the plates, not from the plates themselves. One observer (K. B.) made these measurements. The standard deviations of her estimates from the photoelectric magnitudes of the stars are shown in the fourth column of Table 2. They are close to the standard deviations for the direct eye estimates from the plates (columns 2 and 3 in Table 2) for four of the seven plates (NA4314, 4346, 5243 and 6253). For the three other plates they are noticeably larger. The cause of the deviation for the three plates is not clear. It is, probably, due to the individual perception of the observer. The average standard deviation for all the plates (± 0.20 magnitude) is still within the range of ± 0.1–0.2 magnitude we obtained for all the "traditional" methods of measurement (Table 2), and we concluded that scanning with AgfaScan T5000 provided copies adequate for photometry.

In a more accurate investigation, we sent two of our plates (NA7495 and NA8008) to the Space Telescope Science Institute (STScI) to be digitized with their GAMMA scanner, to compare the results with the T5000 scans. GAMMA is a modified PDS 2020 densitometer with a laser as the light source (Laidler *et al.* 1994). Scanning of one plate with a 15-micron resolution on GAMMA takes approximately four hours, to be compared with the 30 minutes on AgfaScan T5000 for a full plate scan with a nominal 10-micron resolution.

Simple visual inspection demonstrates somewhat higher quality (sharper edges) of the star images obtained with the GAMMA. In order to do a more objective, quantitative comparison, we undertook photometry of many stars both in very crowded and less crowded regions of the plates using the XImage software written in IDL by K. Gordon and kindly made available to us by G. Clayton. This software allows for measuring the instrumental magnitude of the star image in an adjustable diaphragm. The sky background can be measured with a ring-shaped diaphragm surrounding the diaphragm with the star image. However, since the two plates used contain a rather crowded star field in Cygnus, we preferred to measure the sky background in the least crowded region of the plate, with the same circular diaphragm that was used to measure the star, and apply the measured value to background subtraction from all the star measurements. The measurements in this part of the projects were done by A. D. Only the results for NA7495 plate are discussed below, because this plate has considerably better star images (better guiding).

We first measured, on both the GAMMA and the T5000 scans, the relative instrumental magnitudes (relative to the same, arbitrarily chosen reference star) of three groups of stars—faint, medium, and bright—in the open cluster NGC 6819. Table 3 gives the standard deviations of the measured relative magnitudes from the relative photoelectric *B* magnitudes published by Auner (1974).

The bulk of the large values of the standard deviations for both the GAMMA and T5000 scans can be attributed to the systematic effects, such as the nonlinearity of the characteristic curve of the emulsion, the differences between the photographic and the photoelectric *B* system, and the limited size of the diaphragm in our simple measuring procedure, which cuts off an increasingly larger part of the image with the increasing brightness of the star. However, the values of the standard deviations are systematically larger for the T5000 scans and, since the original was the same for both scans, we must attribute these larger deviations to the lower quality of the T5000 scans, which also follows from direct eye inspection of the scans. With this in mind, we will consider the GAMMA scans as "ideal" and use them as a reference to investigate the systematic and random deviations on the MMO scans.

The relative magnitudes of 34 stars on the T5000 scans versus those on the GAMMA scans for the crowded star field in NGC 6819 are shown in Figure 1 and for a less crowded field in Figure 2, together with a second order polynomial fits to the points. The deviation of the graphs from the 45° linear dependence, systematically increasing towards brighter stars, can be attributed to the measuring procedure. The diaphragm of a limited size we used to measure all the stars cuts off a larger and larger part of the star image when we proceed from the fainter to the brighter stars. With the extended, linear lamp as the light source in the T5000 scanner (as compared with the laser beam in the GAMMA microdensitometer), there must be considerably more light scattered on the star images, which should make the images progressively larger (as compared with the GAMMA images) with the increasing brightness of the star. Therefore the effect of the diaphragm cutoff and the ensuing relative depression of the count on brighter stars mentioned above should be stronger for the T5000 scans. This systematic deviation can, however, be mitigated, if not completely eliminated, by an accurate determination of the optimal diaphragms or by using the reduction procedures for crowded star fields (like the daophot package in IRAF). The systematic differences between the working and the reference photometric systems can be taken into account by the usual procedure of constructing the characteristic curve of the working system with the aid of a series of standard stars measured accurately in the reference system.

More important is the additional random noise introduced by our scanning procedure, because this noise cannot be eliminated by any improvements in the measuring or reduction procedure. The additional noise can be quantitatively estimated as the standard deviation of the points on the graphs Figures 1 and 2 from the best polynomial fit to the points. The standard deviation for all the stars taken together is between 0.07 and 0.08 magnitude for both star fields.

Figure 3 shows the results of linear regression to the points representing two separate groups of stars, the bright stars and the stars of average brightness from Figure 2 (the statistics for the group of five faintest stars is too poor to apply a regression). The standard deviation for both these groups taken separately drops to ±0.05 magnitude. Since a part (although, evidently a smaller part) of the scatter of the points on the T5000 versus GAMMA graphs must be due to the GAMMA scans, we can consider ±0.05 magnitude as an upper limit of the rms noise introduced by the scanning on T5000, for the average and bright stars on good plates. This value can be considered as the achievable precision of the photometry on a plate copy digitized with a commercial scanner of the class of AgfaScan T5000.

It is also seen in Figure 3 that the slope of the linear fit for the stars of average brightness is considerably closer to unity and the value of the y intercept is closer to zero than for the group of the bright stars—the effect mentioned above and explained by the systematic increase of the cutoff of the part of the image toward the brighter stars in our simple measuring procedure.

5. Conclusions

Old photographic plates remain an important source of information on the light curves of variable stars from the end of the 19th to the end of the 20th century.

For the plate quality typical for the MMO collection, the "traditional" methods of star brightness measurement (eye, microphotometer, and computer reduction of a CCD copy) are comparable in precision: ± 0.1–0.2 magnitude.

Commercially available scanners of the class of AgfaScan T5000 provide digital copies of the plates allowing for photometry with a precision as high as ± 0.05 magnitude. They can, therefore, be recommended for the digitization of the plate archives, as a good compromise between the time and cost, on the one hand, and the quality of the scanned copies, on the other.

6. Acknowledgements

The authors thank Dr. B. McLean for scanning for this project two MMO plates with the STScI GAMMA microdensitometer, Dr. G. Clayton for help with measuring the scanned images with the XImage software, and Dr. P. Boyce for discussion and advice on the project and valuable suggestions on the manuscript. This project was supported by the NSF (REU) grants AST-9300391, AST-9820555, AST-0097694, and AST-0354056 while K.B., A.D, C.S., and F.T. were REU interns at the MMO.

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Table 1. The major merits and demerits of the three traditional methods of star measurements on photographic plates.

Method	*Merits*	*Demerits*
Eye on the plate	Very fast method.	Comparisons of distant stars and stars differing largely in magnitude were not possible. Background effects cannot be accounted for.
Microphotometry	Comparison of distant stars and stars differing largely in magnitude possible.	A rather slow method. Background effects cannot be accounted for. A microphotometer is needed (no longer in production).
CCD Digitization + IRAF	Comparison of stars differing largely in magnitude possible. Background effects can be accounted for.	Sophisticated hardware and software required. Losses of information due to rephotographing. Limited field of view.

Table 2. Standard deviations of the measured (instrumental) star magnitudes from photoelectric magnitudes for different methods of measurement. Observers are indicated with their initials.

Plate Number (NA)	*Eye on plate, F.T.*	*Eye on plate, C.S.*	*Eye on T5000 scan, K.B.*	*Microphot. F.T.*	*Microphot. C.S.*	*IRAF on CCD image, C.S.*
4314	0.21	0.11	0.19	0.16	0.20	0.10
4346	0.14	0.10	0.16	0.16	0.14	0.17
4463	0.12	0.13	0.24	0.24	0.14	0.13
5243	0.10	0.11	0.13	0.23	0.16	0.15
6253	0.15	0.10	0.15	0.12	0.13	0.15
6270	0.11	0.09	0.34	0.25	0.18	0.16
8370	0.10	0.09	0.20	0.12	0.21	0.16
Average	0.13	0.11	0.20	0.18	0.17	0.14

Table 3. Standard deviations of the GAMMA and T5000 instrumental relative star magnitudes from the photoelectric values obtained by Auner (1974).

Star Group	*Scanner*	*Standard Deviation*
Bright	GAMMA	0.73
	T5000	1.09
Average	GAMMA	1.40
	T5000	1.90
Faint	GAMMA	2.25
	T5000	2.83
All Stars	GAMMA	1.54
	T5000	2.01

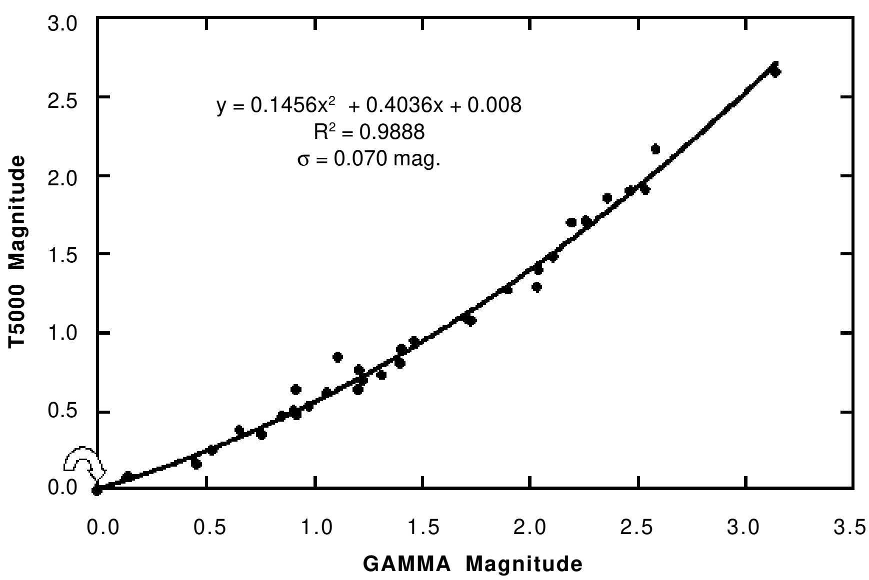

Figure 1. Relative instrumental magnitudes from the T5000 scans of a crowded field in NGC 6819 on the plate NA7495 plotted against those from the GAMMA scans. The solid line is a 2nd order polynomial fit to the points. The arrow marks the reference star.

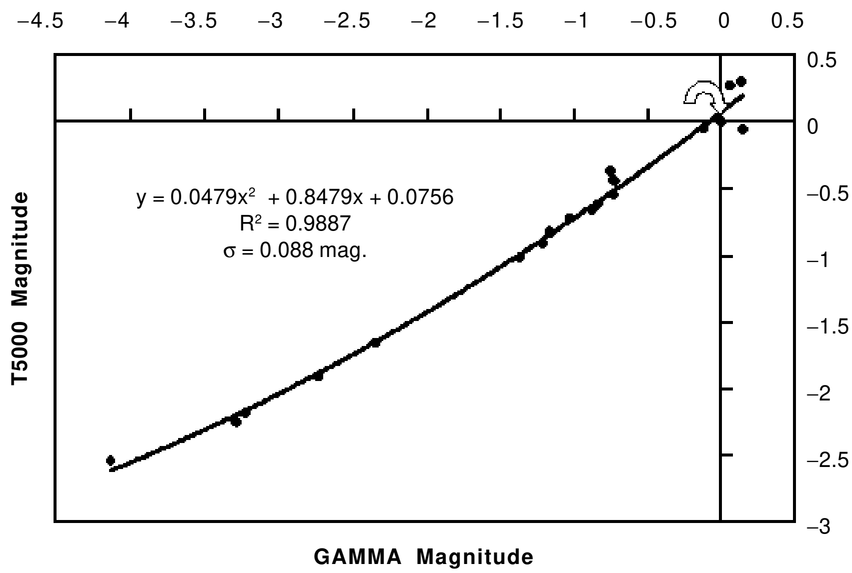

Figure 2. Same as in figure 1, but for a less crowded field. The arrow marks the reference star.

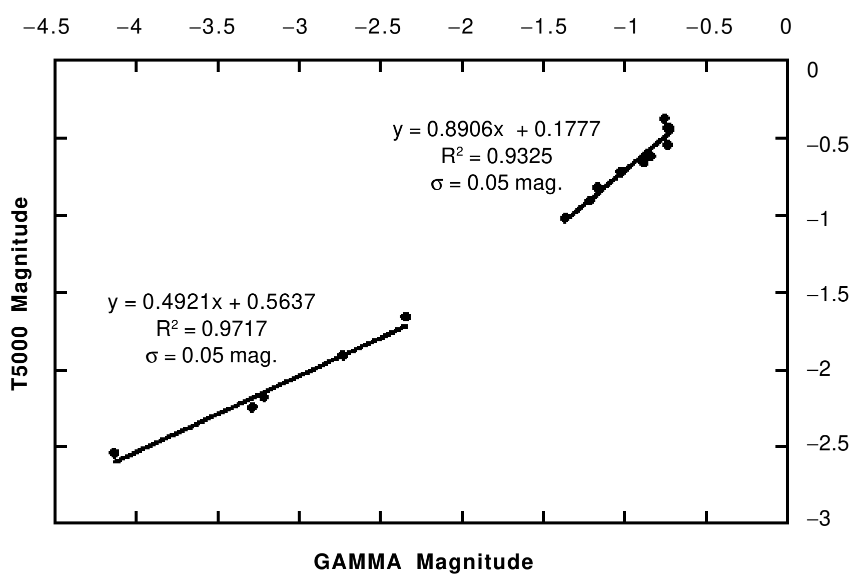

Figure 3. Linear fitting to the points in figure 2 representing bright and average stars.