CCD PHOTOMETRY OF BRIGHT STARS USING OBJECTIVE WIRE MESH

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ABSTRACT

Obtaining accurate photometry of bright stars from the ground remains problematic due to the danger of overexposing the target and/or the lack of suitable nearby comparison stars. The century-old method of using objective wire mesh to produce multiple stellar images seems promising for the precise CCD photometry of such stars. Furthermore, our tests on β Cep and its comparison star, differing by 5 mag, are very encouraging. Using a CCD camera and a 20 cm telescope with the objective covered by a plastic wire mesh, in poor weather conditions, we obtained differential photometry with a precision of 4.5 mmag per two minute exposure. Our technique is flexible and may be tuned to cover a range as big as 6–8 mag. We discuss the possibility of installing a wire mesh directly in the filter wheel.

Key words: methods: observational – stars: individual (β Cep) – stars: oscillations – stars: variables: Cepheids – techniques: photometric

Online-only material: color figures

1. INTRODUCTION

Renewed interest in studies of bright stars, in general, stems from their suitability for long term spectroscopic monitoring with modest telescopes for asteroseismic purposes. As a byproduct of the extra-solar planet quest, a new generation of fiber-fed echelle spectrographs emerged which are capable of measuring the radial velocities of bright stars with an accuracy of meters per second. This opens a new window for studies of multiple the radial velocities of bright stars with an accuracy of meters per second. This opens a new window for studies of multiple the radial velocities of bright stars with an accuracy of meters per second. This opens a new window for studies of multiple the radial velocities of bright stars with an accuracy of meters per second. This opens a new window for studies of multiple.

Moreover, our tests on β Cep and its comparison star, differing by 5 mag, are very encouraging. Using a CCD camera and a 20 cm telescope with the objective covered by a plastic wire mesh, in poor weather conditions, we obtained differential photometry with a precision of 4.5 mmag per two minute exposure. Our technique is flexible and may be tuned to cover a range as big as 6–8 mag. We discuss the possibility of installing a wire mesh directly in the filter wheel.

2. METHODS

2.1. Instrument Setup

We employed two small instruments. First was the 10 cm f/5 guide telescope on top of the 0.7 m Alt-Az Poznan Spectroscopic Telescope 2, fitted with the SBIG ST-7 camera (hereafter PST2G, see www.astro.amu.edu.pl/GATS for general reference). The metal mesh with 0.1 × 0.1 mm pitch and 0.06 mm wire width was fitted on its V filter. Second was a 20 cm f/4.4 Orion Optics Newtonian telescope on a Celestron CGE Pro equatorial mount, equipped with the SBIG ST-8 camera (hereafter Orion). The plastic mesh with 1.5 × 1.5 mm pitch and 0.5 mm wire width was fitted on its objective. Both telescopes were located in Poznań University Observatory park, 65 m above sea level in downtown Poznań, a city of 0.5 million inhabitants. The local astro climate is mediocre at best, affected by the surrounding city, with unstable extinction, often significantly different between western and eastern skies.

The purpose of the mesh was to produce multiple stellar images so that the first- or second-order diffraction images of bright stars became properly exposed while their zero-order images remained overexposed in order to reveal zero-order images of comparison stars at a comparable signal-to-noise (S/N) level. Diffraction of light of the bright stars on the wire mesh produced multiple diffraction images that were roughly separated by 1.9 and 1.2 arcmin, respectively, for PST2G and Orion at the image scale of 3.71 and 2.11 arcsec pixel⁻¹ (Figure 1). The perpendicular wires and corresponding diffraction patterns are not necessary for our purposes, except that they ensure the mechanical stiffness of the mesh and allow wider selection of nth order diffraction images. Orion observations were made through the R filter and exposed for 150 s, PST2G observations were made fixed. His idea applied either for the direct images of the sky or for images of the calibration source exposed on the edge of the plate. However, as far as we are aware, no images of the sky taken through wire mesh were reported in the electronic age of astronomy.
through the V filter and exposed for 10 s. A rotation of the mesh was introduced for the charge bleeding from saturated pixels of the central image not to interfere with the diffraction orders of choice.

2.2. Diffraction Physics

Let us consider a grating of $N$ parallel wires of diameter $\epsilon$ separated by distance $d$. Their diffraction pattern corresponds to that of $N$ slits of width $\delta = d - \epsilon$,

$$I_1(x) = \frac{I_0}{N^2} \left[ \frac{\sin(\pi x \delta / \lambda)}{\pi x \delta / \lambda} \sin(N \pi x d / \lambda) \right]^2,$$

where $I_0$ denotes intensity observed without grating (i.e., for $\delta = d$), $x$ is the angle with respect to the normal to the grating and $\lambda$ is wavelength (e.g., Crawford 1968). Maxima (fringes) are observed when the second denominator vanishes, i.e., when $x$ satisfies $xd/\lambda = m$, where $m$ is an integer. Therefore, the angular separation of fringes in radians is

$$\Delta x_1 = \frac{\lambda}{d}.$$  

For narrow slits, $\delta \ll d$, the first factor remains close to one and all maxima appear to be of comparable height. On the contrary, for thin wires, $\epsilon = d - \delta \ll d$, all fringes except for the central one are fainter by a factor of $(\epsilon/d)^2$. This is because the fringe maxima in the first factor $\sin^2(\pi x \delta / \lambda) = \sin^2(\pi m - \pi x \epsilon / \lambda) \approx (\pi x \epsilon / \lambda)^2$ and the whole factor becomes $(\epsilon/d)^2$. However, for the central fringe, $x = 0$, the first factor remains equal to one.

For a mesh of perpendicular wires, the fringing pattern becomes the product of those in $x$ and $y$ directions, i.e.,

$$I(x, y) = \frac{I_1(x)I_1(y)}{I_0}.$$  

In such cases, the non-central fringes compared to the central one are fainter by a factor of $(\epsilon/d)^4$. Thus, the target-comparison star dynamic range of our method may be increased by the thinning of wires. From Equation (1), it follows that the diffraction fringes are quite narrow, $\Delta x_2 \approx (1/Nd) = 1/D$, corresponding to the diffraction on the whole aperture of diameter $D$. In fact, it can be demonstrated that the fringe pattern corresponds to the squared absolute value of the aperture pattern’s two-dimensional Fourier transform. In particular, the first and second factors in Equation (1) correspond, respectively, to Fourier transforms of a single slit of width $\delta$ and $N$ slits of width zero. Any distortions and asymmetries of the individual fringes observed in Figure 1 are consequences of long-range deformations of the wire mesh. However, the observed image constitutes convolution of the diffraction pattern with the seeing profile, hence, the actual diameter of the low-order fringes is determined by seeing. The high-order fringes constitute grating spectra.

In one dimension, a flat grid represented by a real function $f(x)$ yields a symmetric diffraction pattern $P(-X) = |Ff(-X)|^2 = |Ff(+X)|^2 = P(X)$, where $x, X$ denote grid and image plane coordinates. Therefore, the diffraction asymmetry observed in Figure 1 requires the grid function, $f$, to have an imaginary part that corresponds to the phase difference of the incoming plane light wave falling on different sections of the grid. This happens for the grid tilted/warped out of the flat objective plane perpendicular to the optical axis, say by several light wavelengths.

3. RESULTS

$\eta$ Bootis is a $V = 2.68$ mag star of spectral type G0IV that has been extensively studied with the Microvariability and Oscillations of Stars telescope (MOST) satellite in pursuit of its solar-like oscillations (Guenther et al. 2007). It exhibits no variability above 0.0001 mag. Using PST2G, we obtained 173 frames and reduced them using standard photometric routines.
with Starlink package scripts, including correction for bias, dark current, and flat field. Differential aperture photometry of the first order diffraction image of $\eta$ Boo and the zero-order image of the nearby $V = 7.1$ comparison star GSC 1470-0590 yielded standard deviation of individual measurements of 0.026 mag. Binning of each 15 measurements, lasting 3.5 minutes, yields reduced $\chi^2 = 1.89$ for 10 degrees of freedom and standard deviation 0.009 mag, with respect to a constant. It seems that field rotation coupled with wire mesh geometry imperfections (as discussed in Section 4) did not affect photometric results significantly.

For further tests, as the bright program star $\beta$ Cephei ($V \approx 3.2$ mag), we selected the archetype of a class of multiperiodic pulsating stars. Using the Orion telescope, we obtained 150 frames and reduced them the same way as in the case of $\eta$ Bootis. We used elliptical apertures to measure the target star first-order diffraction images and circular apertures for central (zero-order) images or reference stars GSC 4465-0481, $V = 9.0$ and GSC 4465-0882, $V = 8.2$ (marked in Figure 1 as Ref 1, and Ref 2, respectively).

In Figure 4, we plot magnitude difference Ref 1–Ref 2 covering an interval of about six hours. No trend larger than the unweighted standard deviation of 0.006 mag is present. In Figure 2, we plot magnitude difference, $\beta$ Cep1–Ref 2. To derive an external error estimate, we fitted data with a Fourier series of three harmonics, and for 141 degrees of freedom we obtained reduced $\chi^2 = 1.16$. The unweighted standard deviation in the plot is 0.0045 mag. Since the comparison star is redder than the
target star \((B-V)_{\text{Ref2}} = +0.22\), \((B-V)_{\beta\text{Cep}} = -0.22\) and air mass is growing, we attribute a slight linear trend in residuals at the level of 0.6 mmag hr\(^{-1}\) to differential extinction.

Inspection of Figures 1 and 3 reveals that the diffraction images’ intensity and geometry are distorted in different ways, reflecting the imperfect geometry of the wire grid. The two geometries are related by Fourier transform, hence the image intensity ratio remains fixed for a fixed mesh pattern. For proper aperture centering, the shift of magnitudes between diffraction images remains fixed too. In particular, the long-scale translation and wire thickness asymmetry yield a constant magnitude shift at the level of 0.6 mmag hr\(^{-1}\) air mass is growing, we attribute a slight linear trend in residuals.

Errors in Figures 2–4 appear consistent with independent white noise. Namely, the application of additivity of error squares to Figure 3 yields the standard error of a single measurement of \(\beta\) Cep as \(\sigma_\beta = 0.0025/\sqrt{2} = 0.0018\) mag. If so, then from Figure 2 the error of the comparison star is \(\sigma_c = \sqrt{\sigma_\beta^2 + \sigma_\beta^2} = 0.0041\), consistent with an independent estimate from Figure 4 \(\sigma_c = 0.006/\sqrt{2} = 0.0042\).

To evaluate the effect of variable seeing, which should affect each diffraction order differently, we compared the first and the second diffraction image of the target star. For two diffraction images of \(\beta\) Cep, marked in Figure 1, the standard deviation of magnitude difference does not exceed 0.0025 mag and neither do any trends (Figure 3). Thus, changes in seeing affect our results by no more than 0.0025 mag. Similar results are obtained for other combinations of pairs selected from diffraction images close to the center, therefore, we conclude that our diffraction image photometry remains little affected by variable seeing.

4. CONCLUSIONS

Several approaches have been utilized in the past for obtaining accurate photometry of bright stars using CCD detectors.

1. Alternate long and short exposures—prone to a residual bulk image on the CCD chip and atmospheric condition changes. Additionally, short exposure times are heavily affected by scintillation.

2. The snapshot observation technique (Mann et al. 2011)—requires precise and multiple telescope slews and is sensitive to atmospheric condition changes. Both (1) and (2) require photometric conditions.

3. Covering a fraction of the detector with a neutral density filter reduces useful telescope field of view by introducing a “penumbra” area and, for a given filter, yields limited dynamic range.

The objective wire mesh technique described in Section 2 suffers from none of these drawbacks and produces useful CCD dynamic range between the target and the comparison star of up to at least 5 mag, depending on selection of an appropriate fringe of the target star. Even a wider range of magnitude differences should be available by the thinning of mesh wires, so that the low-order fringes become fainter. Thus, our technique combined with the appropriate exposure time permits the free choice of the comparison star to meet such criteria like scintillation time averaging or appropriate filling of the CCD pixel well. Results of Section 3 demonstrate that in this way excellent photometric precision may be reached in poor climate with inexpensive equipment. The immediate application of our technique would be for ground follow-up observations for the BRITE constellation of satellites. Space photometry may reach several orders of magnitude better precision than that possible from the ground. However, due to reliance on mechanical devices for accurate pointing, its time span is limited as is frequency resolution. Thus, for sufficiently large amplitude oscillations, ground observations still remain useful.

The wire mesh does not have to be installed on the objective. It may be convenient to place it directly on the photometric filter. In that case the mesh cell size should be reduced proportionally to the \(a/f\) ratio, where \(f\) is the telescope effective focal length and \(a\) is the distance between the mesh and the image. With an internal wire mesh each star fringe pattern is created by a different mesh section; however, with a proper telescope tracking and non-rotating field of view this should always be the same section for a given star. Therefore, the relative intensity of
diffraction fringes is preserved, making relative photometry still possible, but it differs from star to star which prevents accurate photometric calibration. Our test of this wire mesh technique variant seems encouraging, but this concept requires further investigation.

The wire mesh technique could be useful not just for BRITE follow-up observations, but could also provide parallel photometric observations for high resolution spectroscopic observations with larger telescopes, e.g., similar to our PST2 project.

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