Photometry of Betelgeuse at daylight

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This is an overview of the requirements for photometric observations of Betelgeuse at daylight. Amateur astronomers with the right equipment can do some significant contributions to the astrophysical science. Experience in photometry is needed, some experience in planetary imaging can be helpful.

Observation period and weather

The daylight observations of Betelgeuse should start at in March and end at Mid September. From May to August the weather conditions should be favorable with many clear and dry days.

Equipment

Telescope:
Preferable Newtonian with aperture of 15-25cm, F/4 – F/5. Refractors with apertures from 10-15cm (F/8-F/10) may be suitable as well. SC telescopes with apertures of 15-25cm (with reducer) may be used too. The focus length should be between 500 and 1500 mm.
Focuser: Motorized focus with stored focus positions is helpful.
Sun filter: For positioning and focusing with the sun a solar filter is required.
Flat field lightbox: For making flat fields this can be helpful. Daylight flats can be made also using a diffuser at top of the scope (e.g. white T-shirt or thin foam plate).
Sun shade: The optical tube should be fitted with a cylindrical sun shade extending 30-50 cm (about twice the size of the aperture) beyond the aperture. This can be made from black paper, painted outside with white paint. Together with a secondary shade (for Newtonian) around the focuser aperture, the shielding should permit pointings as close as 10 degrees to the sun. To prevent heating of the camera, the top of the telescope can be shielded also. Fig. 1 shows my own telescope (25cm Newtonian).

Fig. 1: 25cm Newtonian with sun shields

Mount:
Stable go-to-mount (equatorial or alt-azimuth), preferable on a fixed stand; a pointing accuracy of +-2 arcmin should be achieved. Encoders on both axes would be helpful.

Camera:
Cooled monochrome CMOS cameras with fast USB3 output are preferred. Planetary cameras without cooler may be used too, if dark frames are taken for each observation, own tests with ASI 178MM (without cooling) were successful. The whole field of view should be large enough for easy finding a star, e. g. in the order of around 30 arcmin. The ADC should have 12-16 bits, 14-16bit preferred. CCD cameras with electronic shutter can be used, but the readout of images takes much more time. A high full well capacity is advantageous.
Here is a table with some cooled cameras, which can be used (I can not guarantee for correct values):

Camera	Sensor	Field of view (f=1000 mm) arcmin	ADC bits	Full well capacity	USB
Altair Hypercam 115M, ZWO ASI294MM Pro, QHY 294 Pro	Sony IMX492	65' x 44'	14	65 ke	3
Altair Hypercam 26M, ZWO ASI 2600MM Pro, QHY 268M	Sony IMX571 M	81' x 54'	16	51 ke	3
Altair Hypercam 183M Pro, ZWO ASI 183MM Pro, QHY183M	Sony IMX183	46' x 31'	12	15.5 ke	3
QHY 178M cool	Sony IMX178	25' x 17'	14	15 ke	3
QHY 174M cool	Sony IMX174	38' x 24'	12	32 ke	3

Table 1: CMOS cameras

Camera	Sensor	Field of view (f=1000 mm) arcmin	ADC bits	Full well capacity	USB
ATIK 460exm, Starlight Xpress Trius Pro SX694	Sony ICX694	43' x 34'	16	18 ke	2
Starlight Xpress Trius Pro SX825	Sony ICX825	31' x 23'	16	24 ke	2
Starlight Xpress Trius Pro SX814	Sony ICX814	43' x 34'	16	12 ke	2

Table 2: CCD cameras

Filters:
To get photometric results, which are comparable to other observations, it is necessary to use a photometric V-Filter, e. g. the Baader V-Filter:
https://www.baader-planetarium.com/de/filter/photometrische-filter/ubvri-bessel-v-filter-%E2%80%93-photometrisch.html

It is essential to reduce the light intensity by a neutral density filter with about 1 percent transmission (ND 2.0 or similar), e. g. the Baader filter ND1.8 (1.5% transmission):
https://www.baader-planetarium.com/de/filter/polarisation-neutraldichte/neutraldichte-(grau-)filter-nd-06--09--18--30.html
The Baader ND filters have a very constant transmission over the visible spectrum and can be combined with the photometric V-Filter; the transmission curve of the V-Filter remains practically unchanged.

The ND filter should be placed ahead of the V filter, this prevents damage of the photometric filter, if the telescope is positioned for longer time to the sun (by mistake).

Software

Most telescope and imaging software tools can be used.
For automated procedures my own software "starpilot" ((https://sternwarteebersheim.astronomie-mainz.de/software)) can be used.
For processing images (e.g. stacking) the program "Fitswork" is recommended:
(https://www.fitswork.de/software/softw_en.php)
For photometry my program "fitsmag" (https://sternwarteebersheim.astronomie-mainz.de/software/fitsmag) may be used.

Observations

Finding a star at daytime

To find a star in daylight, first the telescope coordinate system must be calibrated (except it has absolute encoders and is already calibrated), preferable in the night before the observation. At daylight at least the position of the sun can be synced (with a sun filter).
The focus position should be set before search of a star, because the contrast between a defocused star and the sky is very low; this can be done again with the filtered sun image.
Important advice: Don't look into the sun, if the star is near to the sun; don't use a finder scope!

Image acquisition

To get a good signal to noise ratio (SNR), a series of FITS images is acquired (in 16bit mode!) and stacked together. The resulting images must be dark and flat corrected. The total exposure time should be 10 sec or more.
It is reasonable to do the stacking in groups:
The initial stacking can be done automatically (stacking without aligning the frames) for 1 or 2 seconds, about 10 of these stacks are stored (after dark and flat correction) for later processing (with aligning).
This can be done e. g. by the "firecapture" software (http://www.firecapture.de/) or by my own software "starpilot" (https://sternwarteebersheim.astronomie-mainz.de/software/) or the software provided by the camera manufacturer.

Important hint: If automatic stacking (or "live stacking") is used, the resulting stacked images should a be a 32 bit sum or a 16 bit mean value of the original images without scaling. Some apps (e. g. SharpCap) do a scaling of the pixel counts, so that the maximum pixel has always the same value (max. of 16bit or 32bit); with this data photometry is not possible. In this case all raw images must be saved first.

The exposure time for a single exposure depends mainly on the maximum brightness of the sky. The ADUs of the sky should not exceed about 40% of the saturation ADUs. Therefore a test exposure at the brightest sky (at the star nearest to the sun) should be done in the beginning. With the ND filter of 1.5% transmission the exposure will be in the range of 20-150 ms. The same exposure must be used for all star images (Betelgeuse and comparison stars). In addition, a test exposure of the brightest star (may be Betelgeuse or Rigel) should be done. If the star maximum is near saturation, then the exposure time has to be reduced or a slight defocusing can be done; the FWHM of the stars should be around 10 pixels.
Example of such a procedure for each star:
200 exposures of 50 ms dark- and flat-corrected images; the total exposure time would be 10s in this example.

Comparison stars

Together with Betelgeuse at least 4 comparison stars should be observed, see table 3. Some of these stars can not be used, if they are too close (<20°) to the sun (see table).
In addition, Gamma Ori (Bellatrix) can be used as check star (V=1.637 mag, B-V=-0.224).
The magnitudes (from GCPD catalogue) of the comparison stars differ slightly from the magnitudes in my paper in the JAAVSO (Dec. 2021), where I used the magnitudes from the XHIP catalogue.

star	V-mag (GCPD)	B-V	Distance to sun <20°
β Ori (Rigel)	0.138	-0.030	
α CMi (Prokyon)	0.366	0.432	July 6 – July 30
α Tau (Aldebaran)	0.867	1.538	May 12 – June 20
β Gem (Pollux)	1.143	0.991	June 26 – August 5
β Tau (Elnath)	1.650	-0.130	May 25 – July 3
ζ Ori (Alnitak)	1.740	-0.199	
β Aur (Menkalinan)	1.900	0.077	
γ Gem (Alhena)	1.928	0.001	June 11 – July 20
α Ari (Hamal)	2.008	1.151	April 11 – May 15

Table 3: Comparison stars

To get a good estimation of the extinction constant, the comparison stars should be distributed within a broad range of airmasses, between 1.0 and 2.2, if possible.

Image processing
For each star the series of images is stacked together including aligning the star centers. This can be done by any astro imaging software, e.g. Fitswork (https://www.fitswork.de/software/softw_en.php).

The stacking result can be a sum of the image pixels or a mean value. If the result is a sum and the number of stacked images varies from one to another star, then the result must be divided by the individual number of stacked images (to get a mean value), otherwise the images cannot be compared to one another.

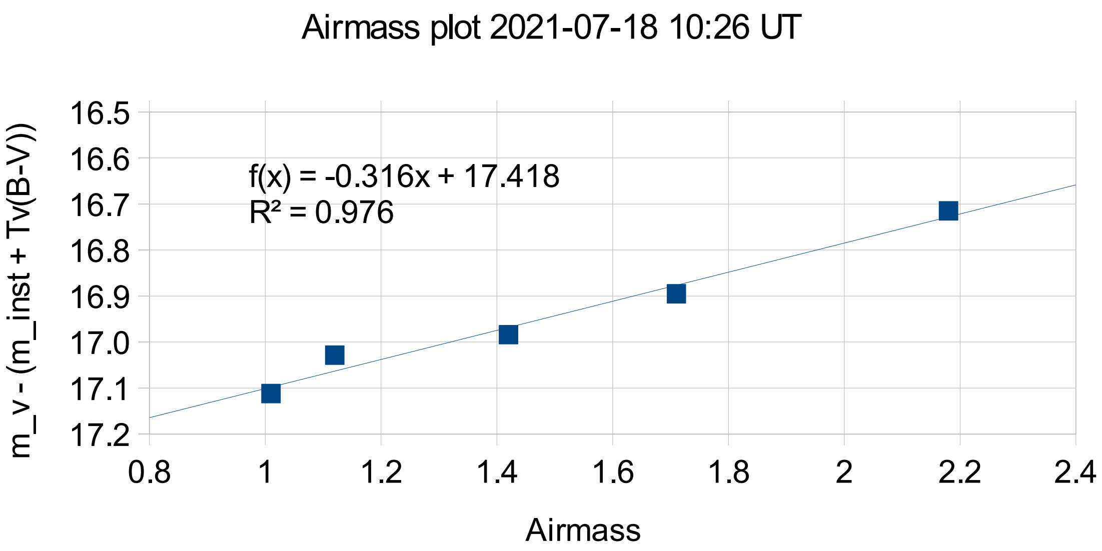
Photometry
As a next step for each star an **instrumental magnitude** has to processed. This can be done by my own software "Fitsmag" (https://sternwarteebersheim.astronomie-mainz.de/software/fitsmag) or by other photometry software.
If aperture photometry is used, the same aperture has to used for each star.

The next step is the calculation of the zero-point magnitude m_0 and the extinction constant k_v. This is done by collecting the instrumental magnitudes and the corresponding airmass of the comparison stars in spread sheet table. An example of such a table is shown here (own observations of July 2021):

Star	m_{inst}	m_v (GCPD)	B-V	Airmass	m_v-(m_{inst}+T_v*(B-V))
α CMi	-16.617	0.366	0.432	1.420	16.984
β Aur	-15.212	1.900	0.077	1.010	17.112
β Tau	-15.379	1.650	-0.130	1.120	17.029
ζ Ori	-15.156	1.740	-0.199	1.710	16.895
β Ori	-16.577	0.138	-0.030	2.180	16.715

The values in the last column are calculated from the catalog magnitude m_v, the instrumental magnitude m_{inst} and the color correction term T_v*(B-V). For T_v a value of -0.0026 was determined.

If the values of the calculated last column are plotted against the airmass values, the points should be positioned more or less on a straight line, as as shown here:



The values for m_0 and kv are derived from a linear regression, which can be taken from the regression line parameters: $m_0 = 17.418$; k=0.316 (negative slope)

From these parameters, the instrumental magnitude m_{inst} , airmass and color index (1.85) of Betelgeuse the standardized magnitude m_v of Betelgeuse can be calculated:

$m_v = m_{inst} + T_v*(B\text{-}V) + m_0 - k_v *\text{Airmass}$

Betelgeuse had $m_{inst} = -16.403$ at an airmass of 1.39, resulting in $m_v = 0.571$

The error of this measurement can be calculated, if the errors of m_{inst} and k_v can be neglected, from the standard error of the linear regression. This can be calculated again in the spread sheet. In the above example this error is 0.027 mag.
For Bellatrix (Gamma Ori) the result in this example was $m_v = 1.594$ (GCPD: 1.637; GCVS: 1.59-1.64)

There are 3 ways of quality control:
The regression coefficient R^2 of the regression line should be >0.90
The standard error of the linear regression should be <0.05 mag
The deviation of the check star magnitude to the catalogue magnitude should be < 0.05 mag.

If one or more of these criteria is not given, there may be several reasons:
(1) Sky is not quite clear (thin clouds)
(2) Exposure too long (saturated pixels)
(3) Camera linearity insufficient or processing errors

To improve the accuracy of the result, a second image acquisition should be taken with the same stars within one or two hours. The magnitude results of the first and second run can be put together into a mean daily value.

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Additional equipment:
To check whether clouds or contrails interfere with the recording, I mounted a reflex camera with a 100mm lens (Canon EOS 450) on the telescope (Fig. 2). A live image from the camera can be displayed on the computer (Fig. 3).

Figure 2: Cloud camera at telescope

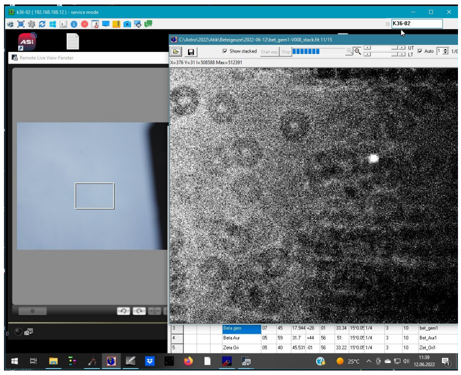

Figure 3: Live image of cloud camera and telescope image

The field of view of the camera is significantly larger than that of the telescopic camera, so that approaching clouds can be recognized in good time.

More information can be found in my paper:
“Daylight Photometry of Bright Stars—Observations of Betelgeuse at Solar Conjunction”
(https://app.aavso.org/jaavso/article/3798/)

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