Crowded Fields Photometry with DAOPHOT

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Abstract   The DAOPHOT method provides an efficient solution to the problem of measuring stellar magnitudes in crowded fields. We present here a detailed description of the method as implemented in IRAF through a worked example on the emission-line star KW97 42-41. In the last chapter we also present, with the support of spectroscopic data, an analysis of the physical properties of the star.

1. Introduction

The usual way of measuring stellar magnitudes is aperture photometry; this method generally gives good results providing that good photometric standard stars are available and that it is possible to define a region around the target star (the annulus) containing mostly sky background. This could be really difficult to define when the target star is located in a very crowded stellar field which is, generally, the case of stars lying on the galactic plane. Moreover, in crowded stellar fields it is easy to find overlapping stellar luminosity profiles. The method of the PSF fitting on stellar profiles implemented by DAOPHOT (Stetson 1987; for its implementation in IRAF see Davis 1994) bypasses these difficulties and allows astronomers (professional and amateur) to get good photometry even in crowded fields. In the following sections we will describe the main features of the DAOPHOT method and its implementation in IRAF by discussing its application to the measure of BVRI magnitudes of a variable star taken from the Kohoutek and Wehmeyer (1997, hereafter KW97) catalogue, a good source of emission-line stars containing more than 4000 stars with suspected emission-lines. (We have written a freely downloadable tutorial which describes in detail all the steps; see the post DAOPHOT on the AAVSO website data analysis forum https://www.aavso.org/daophot).

2. DAOPHOT: a description of the method

A three dimensional surface plot of a CCD frame of a stellar field may look like that represented in Figure 1, where stellar images are similar to mountains emerging from a plain, the plain being the sky background.

Since each point-like image produced by the optics of the telescope is spread mainly because of the atmospheric seeing, any stellar profile has the same shape with the same FWHM (Romanishin 2006). The luminosity profiles roughly follow a
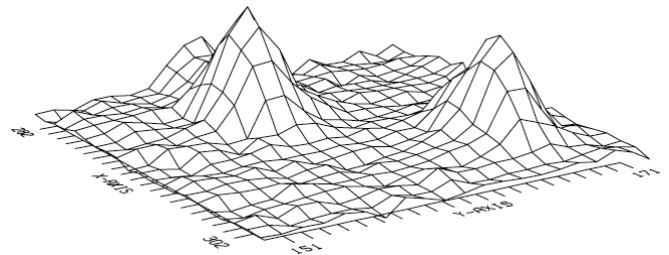

Figure 1. Example of a surface plot of a stellar field.

Gaussian curve centered on the peak and eventually fade into the sky background. As already stated in the introduction, it is generally impossible to use aperture photometry in crowded fields but we can bypass these difficulties by creating an articial stellar profile (the Point Spread Function, PSF) which can be used to identify any stellar feature on the frame. It is therefore possible to measure the instrumental magnitudes within one FWHM for any star. If the comparison stars are on the same frame as the target stars (differential photometry) it is possible to get the standard BVRI magnitudes. The standard BVRI magnitudes of the comparison stars have been probably measured within apertures larger than the value of our FWHM but, since we are comparing stellar profiles of the same shape and width, we can say that, for any filter, the following equation holds:

$$m_{target} - m_{comparison} = M_{target} - M_{comparison} \qquad (1)$$

where m is the instrumental magnitude measured within one FWHM and M is the standard magnitude. On the other hand, if the comparison stars were not on the same frame as the target star (all-sky photometry) we should correct for atmospheric extinction. Moreover, we should measure the instrumental magnitudes within larger apertures because there could be differences in the stellar profiles of the frames. The problem,

now, is to calculate how many magnitudes we should subtract from those measured within one FWHM around the peak of the luminosity profile. Even in a very crowded field it is possible to find a few relatively isolated stars; if they are not isolated enough, we can clean their surroundings by subtracting the PSF from any unwanted stellar feature in order to get more free sky background. The basic idea is to measure the sky-subtracted instrumental magnitudes within regions of increasing radius. The absolute value of the instrumental magnitude to subtract will first show an abrupt growth and then will become constant. Since the outer regions are occupied only by sky background, after a certain distance from the central peak there is no further contribution to the magnitude of the star. This constant limit value is the aperture correction to use. It is crucial, for the method to work, to be able to build a reliable PSF which fits the true stellar profiles.

3. Using DAOPHOT inside IRAF: a worked example

Among the astronomical community, IRAF is a well-known software which, despite its old style interface, is still widely used, maintained, and updated. Among its strong points are a huge number of available algorithms and the possibility to adapt almost any task to the necessities of the user. IRAF tasks are organized into a tree structure, starting from a zero level root directory as in the following example, where any term refers to a collection of tasks or a collection of collections of tasks:

dataio	language	obsolete	softools	vo
dbms	lists	plot	system	
images	noao	proto	utilities	

DAOPHOT is the name of the method developed by Stetson while "daophot" is its implementation in IRAF and, like any other IRAF task, in this paper is written in lower case in quotes. We will use quotes also for keywords used as input by some IRAF tasks.

The task "daophot" is a collection of tasks inside "digiphot", which, in turn, is inside "noao". Here are the tasks inside a typical implementation of DAOPHOT in IRAF:

addstar	daotest	nstar	pexamine	psf
allstar	datapars@	pcalc	pfmerge	psort
centerpars@	findpars@	pconcat	phot	pstselect
daoedit	fitskypars@	pconvert	photpars@	seepsf
daofind	group	pdump	prenumber	setimpars
daopars@	grpselect	peak	pselect	substar

Packages whose name ends with an "@" like "centerpars@" are "wheels within wheels" (Massey and Davis 1992); they use one or more other tasks in order to get the appropriate values for a large variety of parameters.

3.1. Stellar profiles and sky background

The DAOPHOT method needs, first of all, some information about the stellar fields we are going to study. Basically, these are the FWHM of a typical stellar profile and the value of the mean sky background. It is therefore necessary to display the image and to interact with it; generally, IRAF uses DS9 for such a task (SAOImage DS9 at http://ds9.si.edu/site/Home.html; Figure 2)
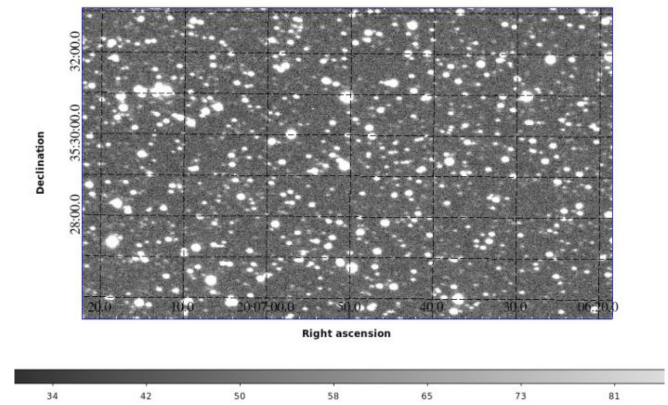

Figure 2. Stellar field around KW97 42-41 (TYC 2679-363-1). CCD R-band filter taken with the AAVSOnet telescope W28 on December 14, 2010. The emission-line star is close to the center of the field, R.A. $20^h\ 06^m\ 50.658^s$, Dec. +35 29' 14.89" (FK5 coordinates at J2000), on the upper-left.
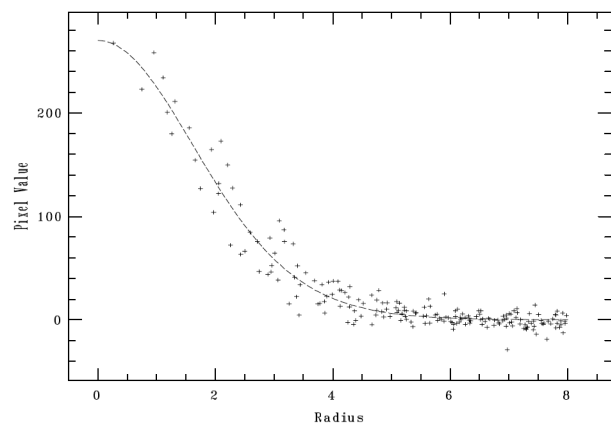

Figure 3. Stellar profile of a star in the field of KW97 39-30. Counts vs. distance from the central peak.

and, once an image is loaded into the DS9, we can interact with it. The task "imexamine" provides information on the FWHM of the stellar profiles and the sky background.

By placing the cursor on a star and clicking "r" we get a radial plot of the luminosity profile (Figure 3) fitted with a Gaussian curve.

The task "imexamine" calculates and displays some parameters of the stellar profile such as the FWHM (for further information see the help of "imexamine" inside IRAF). If the profile of the star is very weak, "imexamine" fails to draw a fit curve. The same task is used to measure the sky background by simply choosing a relatively clean area and pressing the key "m". All these operations should be repeated about ten times and the results should always be written into two text files for further analysis to get good values for the mean FWHM of the stellar profiles and of the mean sky background. (Our tutorial uses some Scilab (http://www.scilab.org/) scripts which ease and speed up some procedures. They are freely downloadable at http://ds9.si.edu/site/Home.html.)

3.2. Finding stars with "daofind"

The next step is to identify all the stellar profiles inside our images using "daofind". This task looks for profiles with the previously calculated parameters and identifies them as stars; it
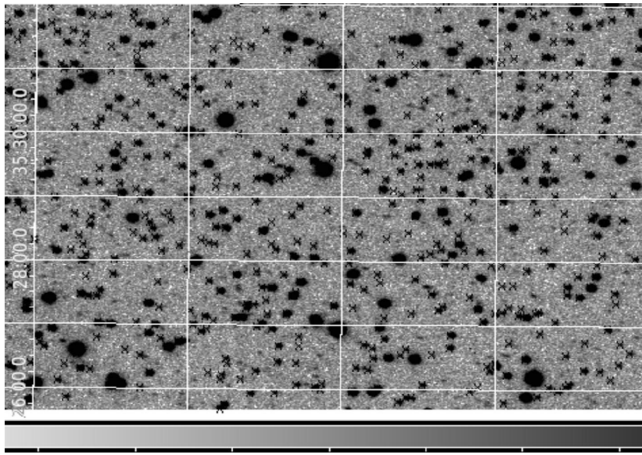
Enlargement of an area of Figure 2 with the stellar profiles identified by "daofind". The image is displayed in inverted grayscale to make the crosses stand out.

discards features too spiky (identified as cosmic rays or warm pixels) or too broadened (maybe some bad regions on the CCD or non-stellar objects like a nebula). Using "daofind", together with the tasks "tvmark" and "display", it is possible to identify any stellar feature by putting a mark (a colored point or a cross) upon it (Figure 4).

We can examine in detail each image with the magnifying glass of DS9 or with "imexamine" for a double check. The image displayed by DS9 immediately reveals whether the vast majority of all the stellar features have been identified.

3.3. First photometry

The following step is to get the instrumental magnitudes within one FWHM of all the stellar features found so far using "phot". This task does a simple aperture photometry within circular regions with a radius of 1 FWHM centered on the peak of each identified stellar profile. It is actually a composite photometry task as it uses other tasks as subroutines to which you can give many input parameters. Generally, the parameters "phot" requires are the radius and width of the annulus used for the photometry and the sky background to subtract. The output of "phot" is a long text file displaying data for any identified stars as in the example below:

```
Bea                    493.791    5.436      1    Bea.coo.1  1
     493.791    5.436     0.000     0.000   INDEF  INDEF   0  NoError
     25.7856            6.701344  4.857022  1464    289    0  NoError
       240.   1.111398      B                  02:46:00
      4.57   1959.753  66.01736  257.4565  24.924   0.239   0  NoError
```

A detailed description of the output of the task "phot" is available in the help of the "phot" task inside IRAF and in our tutorial. Anyway, the basic information hidden inside the preceding table are: i) the image name (Bea); ii) the XY coordinates of the identified star (493.791 and 5.436); iii) the mean sky background around the star (25.7856; iv) airmass, filter and time at the beginning of the exposure (1.111398, B, 02:46:00); v) data on the sky-subtracted countings (257.4565) inside 1 FWHM (4.57 pixels); vi) the measured instrumental magnitude with its uncertainty (24.924 and 0.239). "Bea" is a temporary name used in the data reduction process. It means

that the image was taken using a B filter; it is a diminutive of the Italian name Beatrice.

An INDEF keyword is applied in every field where the task was not able to calculate a value. In order to be sure that "phot" worked correctly, it is possible to use the task "pdump" to make a list of the stars with no photometry (see the tutorial for a detailed explanation); generally, only a small percentage of stars had magnitudes set to INDEF.

3.4. Building the PSF image

The Point Spread Function (PSF) describes how the combination seeing+telescope+detector has spread out the point-like images of the stars. It is necessary to look, in every stellar field, for some (5–10) relatively isolated stars with very few or no neighbor stars and use the task "psf" together with "daopars". This last task is used to give "psf" the correct parameters to build the PSF function. The interaction with DS9 is done by placing the cursor on a chosen star and clicking "a"; Figure 5 is an example of the output.
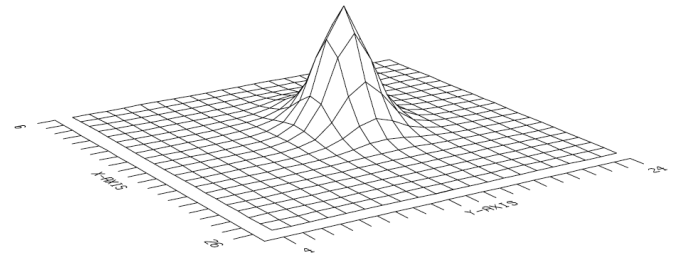

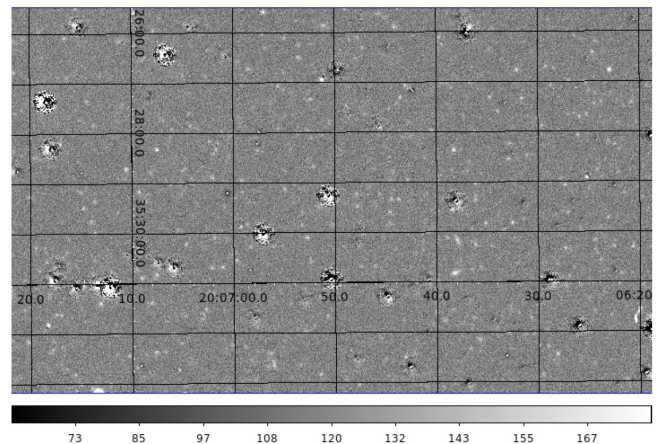Figure 5. An example of a stellar PSF profile.

Figure 6. Stellar field with subtracted PSF profiles; holes are very bright stars not well subtracted.

By typing "a" you decide to use the star to build a stellar profile whereas, if the star is not suitable, you can discard it. After having collected a few acceptable profiles, you can tell the task to build the PSF image of that night and exit. At this point, you may want to check the PSF image built so far and see whether it is a good approximation of the stellar profiles. The task "nstar" is now used to fit the calculated profiles to each star in the field and then "substar" subtracts the calculated profiles from the real stars. The result is shown in Figure 6; the fit is still satisfying even though some very bright stars
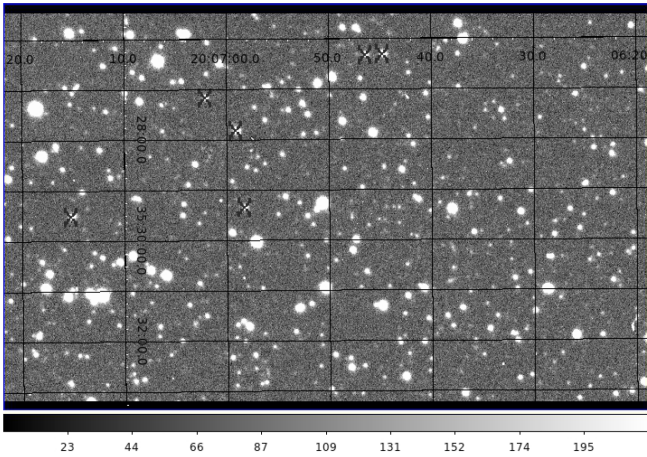
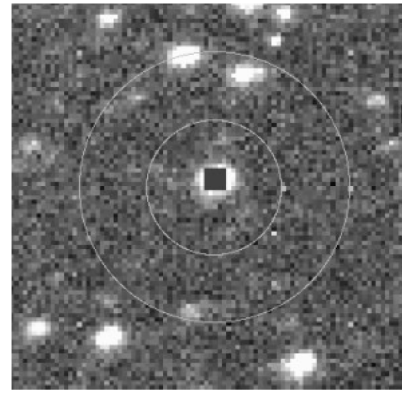Figure 7. Crosses identify the stars used to build the PSF.

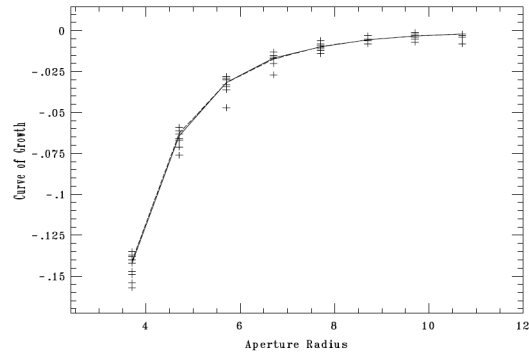Figure 8. An example of a good choice for an annulus-shaped box.

Figure 9. We can see that the fit is converging because the magnitudes measured inside growing regions tend to decrease with increasing apertures, meaning that we are adding less and less star light and more and more sky background; from a certain radius on what we get as starlight is compensated for by what we lose as background.

are not well subtracted. Anyway, if "substar" does not give a satisfactory result, there is the "imedit" task for a cosmetic smoothing process.

The test of the goodness of the cleaning process around the PSF stars can be done by using again "substar" and by creating two frames, one with both the PSF stars and their neighbors subtracted and another with only the neighbors subtracted. DS9 can show the two frames blinking; in order to point out where the PSF stars are, it is possible to previously mark them with "tvmark" (Figure 7).

The final and crucial test of the goodness of the fit is performed by the task "allstar", which subtracts from every single star the PSF profile just calculated. This task is the core of the DAOPHOT method because the fitted profile is used not only to subtract stars from the frames but also to give a better estimate of the stellar magnitudes (see section 3.6). These instrumental magnitudes are then used to get the standard BVRI magnitudes when dealing with differential photometry. We should see that, while bright stars are, generally, not completely erased from the field, PSF stars have disappeared; this means that the PSF profile is a good approximation of the star profiles, at least under a certain brightness. As an example of what IRAF can do, in the next paragraph we calculate the aperture correction even if it is superfluous in the case of differential photometry. If there are no good comparison stars in the same frame as they are too far from our target star, we have to correct for atmospheric extinction and do the aperture correction procedure; the results of the all-sky photometry will not be, generally, as accurate as those we get with differential photometry.

3.5. Measuring aperture correction

The (relatively) isolated stars used to build the PSF are also useful to calculate the aperture correction to apply to any star. Using the output from the task "psf" it is possible to build a file containing information (coordinates, magnitudes, and parameters on the shape of the candidate stars) to give as input to the task "phot". The aim is to perform photometry on PSF stars after having subtracted a certain number of neighbors from their surroundings. Using DS9 it is possible to define an annulus-shaped region centered on the aperture-correction stars that will contain, in addition to the central star, mostly sky

background inside the inner circle and very few or no stars at all in the annulus, as in Figure 8.

The dimension of the annulus is given to the sub-task "fitskypars" while a list of increasing values for the radius of the aperture is given to another sub-task, "photpars" (see again our tutorial for details on the exact syntax of the input parameters to give). The "phot" task evaluates the total amount of countings inside regions with growing radius. Finally, the task to use is "mkapfile". For every PSF star and aperture, "mkapfile" takes the total number of countings previously calculated by "phot", subtracts the sky background, and evaluates an instrumental magnitude. If the algorithm converges the growth curve (from now on GC) of the instrumental magnitudes calculated shows a steep increase at the beginning and tends to flatten as the aperture increases. This is because the increase in the total amount of light is balanced by a growing amount of subtracted sky background. The limit value of the horizontal branch of the CG is the aperture correction to use (Figure 9) and its value is found inside a text file produced by "mkapfile" as output.

3.6. Calculating instrumental magnitudes

The task "allstar" is used again to improve the instrumental magnitudes previously calculated with "phot". The PSF profile is fitted to any identified stellar feature, allowing the user to obtain a better estimate of the countings inside the same aperture (1 FWHM) used by "phot". Another photometry file (its default extension is .als), containing the aperture correction

value, is generated and will be used to give the final estimate of the instrumental magnitudes. This procedure has to be done for every filter. Before the final calculation it is important to correct the errors on the magnitudes by squaring and adding the uncertainties due to the aperture correction using the task "pcalc". All photometry files are to be sorted in ascending order of X coordinates with the task "psort" so that the task "mkobsfile" can create a file with all the useful data. Giving as inputs to "mkobsfile" the *.als* files it is possible to create an output file, called "photometry", where, for any identified star and for any filter used, there are the values of the instrumental magnitudes with their uncertainties. The final step is to extract from the photometry file only data referring to the target star and to the comparison stars.

3.7. Transforming to the standard system

The transformation from instrumental magnitudes to the standard BVRI, but, in the case of KW97 42-41, BV Johnson and RI Cousins, system is performed following the method outlined by Bruce L. Gary (2002–2006)in "CCD Transformation Equations for Use with Single Image (Differential) Photometry." The results are calculated using the weighted average of the magnitudes and the sigma of the weighted average. Here is an example of the results for KW97 42-41 on the night of 6/29/2011:

B	Ber	V	Ver	R_c	Rer	I_c	Ier
12.227	0.008	12.034	0.004	11.774	0.011	11.448	0.012

It is important to point out that in the field of KW97 42-41 we were able to find 12 comparison stars; as might be expected, with fewer reliable comparison stars the statistical uncertainties would have been higher.

Before giving the final results, we should check the reliability of the comparison stars by controlling whether we were able to reproduce their catalogue magnitudes. This can be done by treating each comparison star, in turn, as the target star and using the remaining comparison stars to calibrate its magnitude. This allows us, first, to discard comparison stars whose luminosities deviate too much from the catalogue and, second, to give a quantitative estimate of the reliability of our photometry by calculating the root mean square of the differences between the catalogue and the measured magnitudes. For instance, we found that in the photometry of 6/29/2011 the faintest comparison star has measured magnitudes which deviate considerably from the ones given in the catalogue; therefore we discarded it from our calculations. The new results are given below:

B	Ber	V	Ver	R_c	Rer	I_c	Ier
12.269	0.008	12.055	0.004	11.826	0.011	11.476	0.012

The root mean square on the differences between measured and catalogue magnitudes for each filter are:

B	V	R_c	I_c
0.030	0.050	0.045	0.083

The final results are calculated by using as uncertainties the combination of the two sigmas calculated above:

Table 1. Data for the light curve of KW97 42-41.

Date of Observation	JD	B	V	R_c	I_c
09/27/10	2455466.683	12.24	12.00	11.75	11.46
10/09/10	2455478.648	12.22	12.01	11.76	11.43
10/11/10	2455480.631	12.23	12.02	11.76	11.43
10/15/10	2455484.635	12.24	12.03	11.77	11.44
10/28/10	2455497.615	12.36	12.13	11.90	11.56
11/05/10	2455505.529	12.29	12.05	11.81	11.40
11/19/10	2455519.574	12.09	11.83	11.42	11.22
12/04/10	2455534.625	12.14	11.86	11.55	11.29
12/14/10	2455544.577	12.28	12.07	11.79	11.50
04/02/11	2455653.901	12.23	12.03	11.75	11.48
04/05/11	2455657.256	12.18	12.01	11.73	11.46
04/12/11	2455664.13	12.20	12.03	11.75	11.46
04/20/11	2455671.852	12.23	12.04	11.75	11.43
04/22/11	2455673.977	12.28	12.05	11.82	11.47
04/28/11	2455679.846	12.22	12.02	11.76	11.44
06/12/11	2455724.775	12.28	12.05	11.79	11.46
06/16/11	2455728.783	12.28	12.07	11.82	11.48
06/29/11	2455741.772	12.27	12.06	11.83	11.48
05/03/11	2455684.905	12.29	12.05	11.82	11.53
05/07/11	2455688.817	12.20	12.03	11.77	11.44
05/16/11	2455697.78	12.32	12.05	11.81	11.38
10/11/11	2455845.57	12.47	12.20	11.97	11.66
10/13/11	2455847.985	12.41	12.18	11.94	11.60
12/01/11	2455896.536	12.23	12.02	11.80	11.53
12/10/11	2455905.584	12.27	12.06	11.82	11.53
12/15/11	2455910.595	12.23	12.04	11.80	11.52
01/05/12	2455931.54	12.36	12.12	11.85	11.57
01/07/12	2455933.541	12.29	12.04	11.81	11.52

$B = 12.27 \pm 0.03$ $V = 12.06 \pm 0.05$ $R_c = 11.83 \pm 0.05$ $I_c = 11.48 \pm 0.08$

4. The emission-line star KW97 42-41

In 2010 we submitted to AAVSO a list of variable star candidates taken from the H emission-line objective prism survey by Kohoutek and Wehmeyer (1997) to be observed by the AAVSOnet robotic telescopes. The data were collected by the AAVSOnet telescope W28 between September 2010 and January 2012 with a SBIG ST-7XME CCD and B and V Johnson and R and I Cousins filters. The emission-line star KW97 42-41 was the first to be analyzed with DAOPHOT. After having discarded poorly guided or out of focus frames, we measured instrumental magnitudes on every frame (see Table 1) and then transformed them into standard BVR_cI_c magnitudes. We present here a rough light curve, that is, raw data plotted without any kind of interpolation (Figure 10). There seem to be changes of about 0.2 magnitude that could take place on a time scale as short as a few weeks. In addition, there may also be a longer term variability on a time scale of several months. We tried a more quantitative analysis using the phase dispersion minimization algorithm (Stellingwerf 1978) as implemented by the IRAF task "pdm". This method
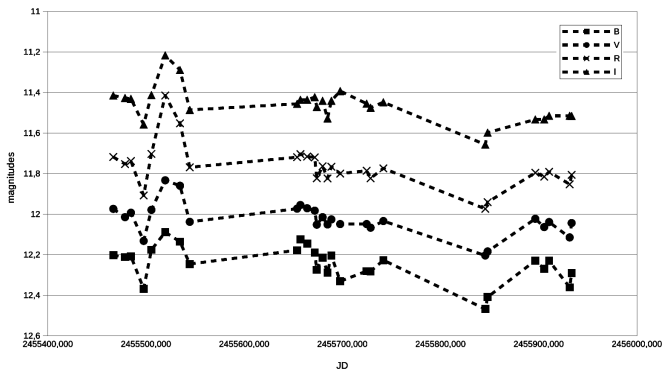
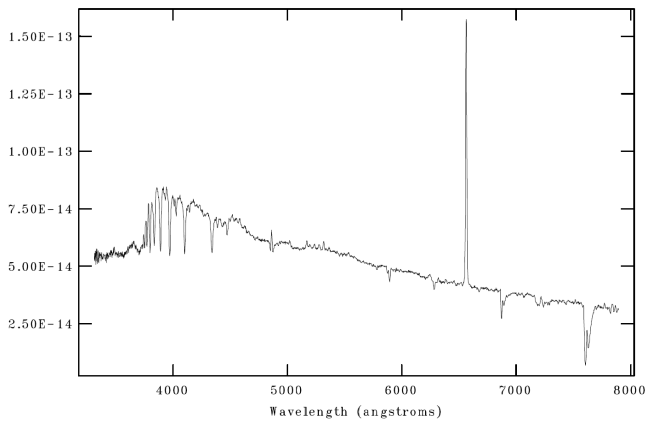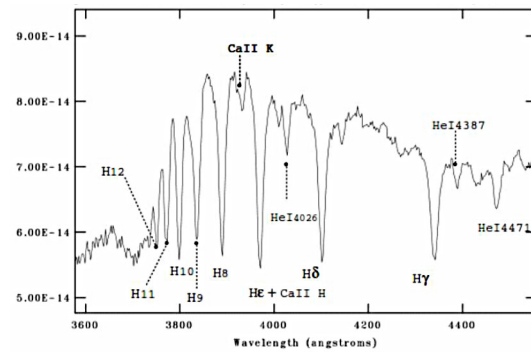Figure 10. The light curve of KW97 42-41. Data: see Table 1.

Figure 12. Blue side of the optical spectrum of KW97 42-41.

Table 2. Equivalent widths (in Å) of some absorption lines.

Star	$H\gamma$	HeI $\lambda 4026$	HeI $\lambda 4471$
KW97 42-41	5.1	1.4	1.8
B2	5.1	1.5	1.4

Figure 11. Optical spectrum of KW97 42-41. This is an average of two 1200-sec exposures, taken with a 300-lines mm^{-1} grating and a Boller and Chivens spectrometer attached to the Cassegrain focus of the 1.22-m "Galileo Galilei" telescope of the Asiago Astrophysical Observatory (Mount Pennar) of the Department of Physics and Astronomy of the University of Padova. Courtesy of Dr. Alessandro Siviero.

Figure 13: An enlargement around H showing its composite profile.

seems to confirm periodicities of about hundreds of days ($\simeq 225$); however, it is important to take into consideration that the number of data available is just enough (28) to make a reliable estimate as specified in the help manual of the task. Moreover, to test the short term variability we would need much more data from close-up observations.

The mean color indexes (with a 3-sigma statistical uncertainty) are: B–V = 0.22 ± 0.09, V–R_c = 0.25 ± 0.06, and R_c–I_c = 0.32 ± 0.13. Since KW97 42-41 has a very low galactic latitude (l = 072.4949, b = +01.7511 J2000), these are not the true color indexes of the star as its light is heavily reddened by the interstellar medium. In order to have some more information on the physical nature of this star, we asked Dr. Alessandro Siviero of the Astrophysical Observatory of Asiago-Pennar to take a couple of medium-resolution spectra of this object (Figure 11). (Siviero 2016)

A strong Hα in emission and a remarkable Balmer series in absorption immediately stand out. Figure 12 shows an enlargement of the blue side of the optical spectrum of the star where it is possible to identify the Balmer series up to H12, the two H and K lines of the ionized calcium, and some remarkable neutral helium absorption lines. The following table shows the equivalent widths of the Hγ, HeI λ4026, and HeI λ4471

absorption lines of KW97 42-41 compared with the values given by Jaschek and Jaschek (1990; p.137). These values suggest that KW97 42-41 belongs to the B2 spectral type (Table 2).

The spectrum reveals not only Hα in emission but also a clear composite Hβ profile (Figure 13) where a strong emission is superimposed on a normal stellar absorption line. All this is consistent with the hypotheses that KW97 42-41 is a Be star seen pole-on (Kogure and Leung 2007).

Finally, we tried to estimate the absolute magnitude of the star. Green *et al.* (2016) implemented a three-dimensional map of the dust in the Milky Way on the website "3D Dust Mapping with Pan-STARRS 1" (http://argonaut.skymaps.info/). By giving the coordinates of an object, the website traces the interstellar reddening (E(B–V) vs. Distance Modulus) along that direction. We calculated a color excess value of 0.46 using the unreddened color index values given by Cox (2000, table 15.7, p. 388), which results in a distance modulus of 12. Knowing this and calculating a mean apparent visual magnitude of 12.1 from our data in Table 1, we obtained a visual absolute magnitude of 0.1 and a distance of 2.51 Kpc. Though fainter than a typical B2 main-sequence star (Cox 2000, Table 15.7, p. 388), the absolute magnitude is consistent with the classification of KW97 42-41 as an early-type emission line star.

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