Optical Photometry
(PRACTICAL SESSION GUIDE)

UC/2011
A. Data and information visualisation. Identification of sources

In the practical session, you will use three frames taken with the Liverpool Telescope in the $g$ and $r$ bands. The first frame is called $Twinr.fits$ (in the directory $ObsAstron$), and its field of view (FOV) is $4.6' \times 4.6'$. The FOV covers a sky region including several point-like sources (stars and quasars), which appear as circles of finite size (atmospheric-instrumental seeing effect).

It is convenient to use a visualisation tool as a first step towards a full analysis of the astronomical data. You will work with the SAOImage $DS9$ application. Once the frame ($Twinr.fits$) is loaded, the tool displays the rough counts in the $1024 \times 1024$ pixels (the pre-processing is done, but the background has not yet been subtracted). On the left-hand side of the $DS9$ screen, astrometric information is available, i.e., equatorial coordinates (right ascension, RA, and declination, $\delta$). Two arrows indicate North and East. The $Zoom$ and $Scale$ functions allow us to study different spatial and bright scales, respectively. Information about the observational setup and some properties of the frame is also available in the “fits header” ($File \rightarrow Display Fits Header$). The “fits header” incorporates the value of $G$ ($e^{-}/count$) (parameter $GAIN$), the pixel scale ("/pixel) (parameter $PIXSCALE$), the average background $b$ (counts/pixel) (parameter $BACKGRD$), the standard deviation of the background (parameter $STDDEV$), and a rough estimation of the FWHM of the seeing disc, in both pixels (parameter $L1SEEING$) and " (parameter $L1SEESEC$). Write in your notebook the values of these six parameters of interest.

Most of the objects in the field of view can be identified from the corresponding finding chart (see Fig. 1). Taking into account the finding chart in Fig. 1, write the rough positions (centres) of the D-H stars, in both equatorial sky coordinates (RA and $\delta$ in degrees) and Cartesian CCD coordinates $(i,j)$. If necessary, rotate the frame to align the North/East directions ($Edit \rightarrow Rotate$).
Fig. 1.- Finding chart to identify objects in Twinr.fits. North is up, East is left. Seven bright stars (F, G, H, E, D, X and R) as well as two quasars (A and B) are indicated.

B. Image quality

The image quality in an optical frame is mainly determined by two parameters: FWHM and S/N. First, the FWHM of the seeing disc is directly related to the spatial (angular) resolution. Two point-like objects very close to each other can only be resolved (i.e., separated as two individual sources) in very good seeing conditions. Second, the signal-to-noise ratio (S/N) within an aperture of radius $R$ informs us about the reliability of the photometry for the object inside the aperture, which has a given magnitude $r$ ($r$-Sloan passband). Thus, the FWHM and S/N play a central role in describing the image quality. You will measure the FWHM of the 2D distributions of light of the relatively bright star H, as well as the S/N for the faintest star R (see section A). To this end, you will work with the Image Reduction and Analysis Facility (IRAF). Firstly, to find information on the $ugriz$ magnitudes of the H star, you can go to SDSS database, i.e., http://cas.sdss.org/astrodr6/en/tools/chart/navi.asp?ra=150.36523&dec=+55.89112. Once you are at this SDSS Web page, look for the panel on the right-hand side and click on the “Explore” button. It appears a new screen containing details of the H star. Then click on “Photo Tag” within the “Photo Obj” menu (left-hand side of the new screen). In particular, the parameters “psfMag_r” and “psfMagErr_r” give you the magnitude and error in the $r$ band. Write (in your notebook) these data.
After opening a DS9 screen and a standard IRAF terminal (prompt cl> or ecl>), you are ready to use the IRAF packages. Depending on the device (PC), these tools may be easily created (by clicking on icons) or may require some additional effort (to type ds9& and xgterm –sb –fn 12x24& on a Linux Console, and to type cl on the xgterm). The IRAF environment consists of several packages (see Fig. 2), and you can obtain help on their use by typing help <package>, e.g., help daoedit or help imexamine. All frames are placed in the folder ObsAstron, so you must go into this directory. Type dir to know the available files in your current directory. You can use cd <dir> to move to another position in the PC directory tree. From the cl> or ecl> prompts, you can access to the main packages noao, images, ... (see Fig. 2) by typing <package>. For example, typing noao, a new prompt no> appears in the standard IRAF terminal. You can then access to the digiphot package (typing di), and then access to daophot (typing da), and so on. Type bye to exit any package. To analyse the astronomical images in a proper way, you must type set stdimage=imt1024.

Fig. 2.- Diagram of the IRAF packages.

To measure the FWHM and other quantities of interest, you must go from cl> to no> (typing noao), di> (typing di or digiphot), and da> (typing da or daophot). Once you are in the daophot environment (DAO
crowded-field photometry package), you can display the frame: type **display Twinr.fits 1** (the frame will be shown on the **DS9** screen). In an initial iteration, you must edit several basic parameters:

1. **How to obtain accurate centres of the distributions of light (stars)?**
   Type `centerpars.calgorithm='centroid'` (the kind of algorithm)
   Type `centerpars.cbox=2 \times L1SEEING` (the length of the sides of the square boxes, which are used to find the centres of the light circles; you know $L1SEEING$, so you must compute $2 \times L1SEEING$ and introduce this numerical value in the **standard IRAF terminal**. Here and below, introduce the $L1SEEING$ value in a 3-digit format, e.g., 3.98 pixels $\rightarrow$ 4.0)

2. **How to determine the background around the stars (sky annulus)?**
   Type `fitskypars.salgorithm='median'` (the algorithm computes the medians, which are used to clean the photometric apertures defined in [3])
   Type `fitskypars.annulus=4 \times L1SEEING + 1` (the inner radius of the sky annuli; you must use the $L1SEEING$ value in the fits header)
   Type `fitskypars.dannulus=2 \times L1SEEING` (the width of the sky annuli; you must use the $L1SEEING$ value in the fits header)

3. **How to obtain the true counts within the photometric apertures (corresponding to the stars) and the associated instrumental magnitudes?**
   Type `photpars.weighting='constant'` (the algorithm gives equal weight to all pixels)
   Type `photpars.aperture=2 \times L1SEEING` (the aperture radius $R$; you must use the $L1SEEING$ value again)
   Type `photpars.zmag=0` (the zero-point term; from $zmag=0$ you simply infer $r_{inst,R} = -2.5 \log C_{r,R}$)

After editing the eight photometric parameters, type **daoedit Twinr.fits**. All things are ready to analyse the optical frame (**Twinr.fits**). First, you must select the **DS9** screen and put the mouse pointer (only put, do not click!) on the H star (in this section, we try to study the H star in detail). You must put the pointer at the estimated central pixel (section A). This rough centre is used to define the box that leads to a refined centre (see [1]). Then, press on the button $r$ in the keyboard. The **IRAF** response is the creation of a new **graphics IRAF terminal**. At this stage, you are working with three different terminals: the **DS9** screen, the **standard IRAF terminal** (to access to directories or packages, introduce parameters, run tasks, etc), and the **graphics IRAF terminal** (to display some graphical outputs). The new graphical output consists of the radial profile of the H star. Check for a right position of the apertures (photometry and
sky; see the vertical lines). At the top, you can also find an accurate (refined) estimation of the centre, two estimations of the background around H (mean and median), the standard deviation of the background, an accurate measurement of the FWHM of the light distribution, and the values of $C_{r,2\text{FWHM}}(H)$ and $r_{\text{inst,2FWHM}}(H) = -2.5 \log C_{r,2\text{FWHM}}(H)$. Select the DS9 screen again, put the mouse pointer on any pixel, and press on the button q in the keyboard (you exit from the daoedit interactive task). Write the new data in your notebook, and compare these and the old ones derived in section A (position of the centre, BACKGRD, STDDEV and L1SEEING). Type `reset stdplot=eps` on the standard IRAF terminal. Type then `gcur`. You must select the graphics IRAF terminal and press on the buttons = (this produces an EPS file containing the radial profile and the rest of data on the graphics terminal) and Ctrl+d (stop) in the keyboard. To complete the “graphics capture” task, type `gflush` on the standard IRAF terminal. Rename the new EPS file in the working directory ObsAstron (→ H1phot.eps).

In a second (last) iteration, you must re-edit the four parameters of the tasks [1-3] that depends on the seeing value. Instead of the L1SEEING value, you must use the new result on the FWHM. Later, type daoedit Twinr.fits again, select the DS9 screen, put the mouse pointer (remember: only put, do not click!) on the new centre of the H star (round coordinates to integer numbers), and press on the button r in the keyboard. The graphics IRAF terminal should displays the radial profile of the star, the re-edited photometric and sky apertures, and re-estimates of the centre, the background (and its standard deviation), the FWHM, $C_{r,2\text{FWHM}}(H)$ and $r_{\text{inst,2FWHM}}(H) = -2.5 \log C_{r,2\text{FWHM}}(H)$. Select the DS9 screen, put the mouse pointer on any pixel, and press on the button q in the keyboard (this allows you to exit from the daoedit task). Compare the centres and FWHMs in both iterations (if there is no change, then you have final results). Capture the information on the graphics IRAF terminal (see above) and rename the corresponding EPS file (→ H2phot.eps).

Determine the FWHM in arcsec (″). Could you visually resolve two point-like objects separated by 1″?. What about a separation of 6″?. Determine the separation between the two quasars A and B.

Study the faintest star (R) using the photometric parameters [1-3] that were set during the analysis of the H star. Write the centre, background (and its standard deviation), FWHM, $C_{r,2\text{FWHM}}(R)$ and $r_{\text{inst,2FWHM}}(R)$. Obtain the corresponding EPS file (Rphot.eps). Determine the S/N. Do you obtain poor ($S/N < 10$) or good ($S/N >> 10$) signal?
Fig. 3.- Example of a photometric output from the **daoedit** interactive task.
C. Instrumental and differential photometry

In the previous section, you derived $C_{r,2FWHM}$ and $r_{\text{inst},2FWHM}$ for the H and R stars. Now, you must get photometric data for other stars that were identified in section A (D-G stars), i.e., $C_{r,2FWHM}(D)$ and $r_{\text{inst},2FWHM}(D)$, $C_{r,2FWHM}(E)$ and $r_{\text{inst},2FWHM}(E)$, $C_{r,2FWHM}(F)$ and $r_{\text{inst},2FWHM}(F)$, and $C_{r,2FWHM}(G)$ and $r_{\text{inst},2FWHM}(G)$. In other words, you must apply `daoedit` on the four stars, using the current parameters of the tasks [1-3] and the rough estimates of the stellar centres in section A (see above). The final product must be a set of 4 EPS files (e.g., `Dphot.eps`, `Ephot.eps`, `Fphot.eps` and `Gphot.eps`). You are assuming that the FWHM of the H star is basically consistent with the FWHMs of the other stars in the FOV. Can you justify this assumption?

Apart from instrumental photometry (which has not a fair astrophysical interpretation), you can also do differential photometry. In particular, there are photometric relations (S = D-G):

$$r_{\text{inst}}(S) - r_{\text{inst}}(H) = -2.5 \log \left[ \frac{C_{r,2FWHM}(S)}{C_{r,2FWHM}(H)} \right] = r(S) - r(H) \rightarrow r(S) = r(H) - 2.5 \log \left[ \frac{C_{r,2FWHM}(S)}{C_{r,2FWHM}(H)} \right],$$

where the $r(H)$ value is reported by the SDSS collaboration (see section B). Determine the true magnitudes of the four stars D-G with their corresponding errors (photometric uncertainties). Compare the measurements and the values in the SDSS database (see section B).
D. Colour-temperature relationship

A typical stellar spectrum approximates a Planck curve (blackbody radiation). Therefore, the emitted intensity varies with wavelength such that a hot star emits more energy at blue wavelengths than at red wavelengths, while a cool star emits mostly in the red spectral region. For a given star, if the photon flux is measured at two different wavelengths, using two filters, then one can obtain the ratio between both determinations. This flux ratio is equivalent to the difference of true magnitudes or colour index, and it is related to the surface temperature of the star (see Fig. 4).

![Fig. 4.](image)

**Fig. 4.** - Surface temperature vs. colour index B-V. B > V (B-V > 0) means that blue photons are not dominant in the stellar light, while B < V (B-V < 0) is associated with blue sources. Bluer stars have greater temperatures.
The system of measuring magnitudes at two different wavelengths, e.g., $g$ and $r$, forms the basis of defining the "colour" of stars. Rather than use words such as red or orange, astronomers define the colour of a star to be its colour index. If, for instance, we use an $r$-Sloan filter, we can measure the true magnitude at $\lambda_r = 6165 \, \text{Å}$ (see section C). A bluer filter provides a second magnitude and thus a colour. For example, the $g$-Sloan filter leads to the magnitude at $\lambda_g = 4686 \, \text{Å}$. The colour $(g-r)$ vs. temperature $(T)$ relationship is

$$f(T) = \left\{ \frac{\exp(hc/\lambda_r kT) - 1}{\exp(hc/\lambda_g kT) - 1} \right\} = 10^{-0.4(g-r)} \left( \frac{\lambda_g}{\lambda_r} \right)^4,$$

which is a transcendental equation. For a graphical solution, one can plot $f(T)$ to find the temperature at which $f(T) = 10^{-0.4(g-r)} \left( \frac{\lambda_g}{\lambda_r} \right)^4$.

You must take the frame Twing.fits (in the directory ObsAstron), identify the E-G stars and perform an analysis similar to that in previous sections in the $r$ band. Going into particulars: measure the true FWHM in the $g$ band, obtain the photometry files $Ephot.g.eps$, $Fphot.g.eps$ and $Gphot.g.eps$, determine the true $g$-band magnitudes of the three stars E-G with their corresponding errors (photometric uncertainties), compare these measurements and the values in the SDSS database (see section B), and determine the colours. Compare the observed colours and those derived from the SDSS magnitudes. Estimate the surface temperature of the three stars.

**E. Intrinsically extended sources**

You must display the additional frame Crossr.fits (standard DS9). Write the average background $b$ (parameter BACKGRD) and its standard deviation (parameter STDDEV) in your notebook. In the new frame Crossr.fits, you can find three bright point-like sources that are seen as circles of light: stars S1-3 in Fig. 5. This similar apparent shape is caused by the atmospheric-instrumental seeing. You can test the similarity of the shapes of different stars in the FOV, and thus, justify their atmospheric-instrumental nature, i.e., they do not trace intrinsic structures of stars.

Within an IRAF session, once the global background is known (see here above), you must subtract it from the frame. To subtract a sky level of $b$ counts from Crossr.fits, and then save the cleaned image as Crossrclean.fits, type `imarith Crossr.fits – b Crossrclean.fits`. Type `display Crossrclean.fits 1` to show this frame on the DS9 screen.
**Fig. 5.** Frame *Crossr.fits*. The new FOV contains a bright (face-on) spiral galaxy, i.e., an intrinsically extended source.

Go from the current prompt to **tv>** (see Fig. 2 and section B). Once you are there (**tv** package), the next step is a rough comparison between the brightness of the three stars, and the extended source in the midpoint between S1 and S3 (see Fig. 5). You can use the **imexamine** interactive task. Type **imexamine**, select the **DS9** screen, and put the mouse pointer (only put, do not click!) on the centre of the S1 star. Then, press on the button **a** in the keyboard. There are several outputs corresponding to this option (**a**), but we are mainly interested in the **PEAK** parameter (peak or central value of the profile, i.e., **PEAK1**). Repeat the procedure using the other two stars S2-3 and the spiral galaxy, and estimate the amplitudes **PEAK2**, **PEAK3** and **PEAKGAL**, as well as the ratios \( \text{rat2} = \text{PEAK1/PEAK2} \), \( \text{rat3} = \text{PEAK1/PEAK3} \) and \( \text{ratgal} = \text{PEAK1/PEAKGAL} \). Selecting the **DS9** screen and putting the mouse pointer on any pixel, press on the button **q** (exit) in the keyboard.
Now you need to edit the parameters for contour plots. Type:

```
eimexam.ncolumns=100  (number of pixels along the x-axis, i.e., ~ 30")
eimexam.nlines=100    (number of pixels along the y-axis, i.e., ~ 30")
eimexam.ncontours=40  (number of isophotes ≡ constant bright lines)
eimexam.floor=2 × STDDEV (minimum level of brightness).
```

After, type `imexamine`, select the DS9 screen, and put the mouse pointer (only put, do not click!) on the centre of the S1 star (see Fig. 5). Then, press on the button e in the keyboard. This last action allows you to visualise the isophotes of the S1 star (contour plot) in the **graphics IRAF terminal**. Selecting the DS9 screen and putting the mouse pointer on any pixel, press on the button q (exit) in the keyboard. Type `reset stdplot=eps` on the **standard IRAF terminal**. Type then `=gcur`. You must select the **graphics IRAF terminal** and press on the buttons `=` (this produces an EPS file containing the contour plot) and **Ctrl+d** (stop) in the keyboard. To complete the “graphics capture” task, type **gflush** on the **standard IRAF terminal**. Do not forget to rename the new EPS file: `S1contour.eps`. Repeat the task with the other two bright sources S2, S3 and GAL (spiral galaxy) in Fig. 5, but normalizing the frame in a convenient way. For example, before to analyse the S2 isophotes, you must re-scale the `Crossrclean.fits` image: `imarith Crossrclean.fits * rat2 Crossrclean2.fits`, and then work on the new frame `Crossrclean2.fits`. Compare (shape and size) the three stellar contours (`S1contour.eps`, `S2contour.eps` and `S3contour.eps`) and the galactic one (`GALcontour.eps`).