AIDA: a software package for 2D model fitting analysis of astronomical images

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ABSTRACT

AIDA (*Astronomical Image Decomposition and Analysis*) is a software package originally developed to analyze images of galaxies with a bright nucleus and to perform the decomposition into the nuclear and the galaxy components. The package is able to perform photometrical and morphological study of faint galaxies as well as standard photometry of stellar fields. With the use of graphical interfaces, AIDA assists interactively the user in selecting sources and preparing them for the analysis. Since the decomposition into the galactic and nuclear components, in particular in the case where the nucleus is dominant, requires a careful characterization of the PSF, AIDA has been designed to manage complex 2-D models (both analytical and empirical, or a combinations of them), even variable in the field of view, making it suitable for Adaptive Optics observations. PSF models can be provided by the user or modeled by AIDA itself using reference stars in the images. Relevant parameters of the target sources are then extracted by fitting source models convolved with the PSF.

In addition to the standard (interactive) mode AIDA can also perform automatic processing of a large numbers of images, extracting the PSF model from each image and evaluating source parameters for targets (stars, galaxies, AGN or QSO) by model fitting. With this automatic mode, AIDA can process, in a fully automatic way, large datasets of targets distributed in several images.

Keywords: Astronomy, Image processing, PSF, Fitting, IDL, Adaptive Optics

1. INTRODUCTION

An astronomical image (*I*) can be described as the convolution of the function describing an astronomical source S and the PSF of the optical system adopted:

$$I = S \otimes PSF$$

Fitting source models convolved with the PSF to images allows estimating the astrophysical parameters of the sources. In the case of stars, S is a δ function and *I* is just the PSF itself: PSF fitting allows recovering information on the magnitude. In fact it is a well known method for doing photometry, particularly useful in crowded fields. Using more complex models for galaxies, it is possible to retrieve information on the morphology. In other cases, the objects can have more components, like the Active Galactic Nuclei which show a nuclear and a galactic component:

$$I = (galaxy + nucleus) \otimes PSF$$

In some cases (quasars) the galactic component can be outshined by the nuclear one, therefore the correct decoupling of the shape of the host galaxy requires a carefully detailed PSF model. AIDA[1] has been originally developed to enable handling this complex difficult problem.

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2. AIDA OVERVIEW

The software is developed in IDL (Interactive Data Language, by ITT Visual Information Solutions[2]), a commercial data analysis environment commonly used in the astronomy and physics communities, which developed specific libraries. The IDL programming language is array-oriented, which makes it very suitable for image processing. IDL is available for the most common computer hardware platforms and operating systems and the source code is, to a large extent, independent on the platform resulting in a single source package. However, the portability is not complete (e.g. the graphical appearance can change, other than, obviously, the calls to the OS are different): for this reason, when run, AIDA recognize the OS under which is working and optimize the features OS-dependent. It has been tested under various Operative Systems: Linux SuSE, Linux Red Hat, Mac OS, Windows XP and 7. The software can run also under Virtual Machine, (no IDL license required). It makes use of widget based GUIs (*Graphical User Interface*) to provide a user friendly interaction with the analysis procedure. However, a "batch" mode (bypassing the graphical interfaces) has been implemented for processing large number of objects.

AIDA was originally developed in the framework of the analysis of QSO images[6-12], but given the large set functionalities it can be used for different applications.

Since the development of this software started, we tried to follow some main guide lines:

- build a user-friendly tool
- highly interactive
- able to provide results with little user intervention
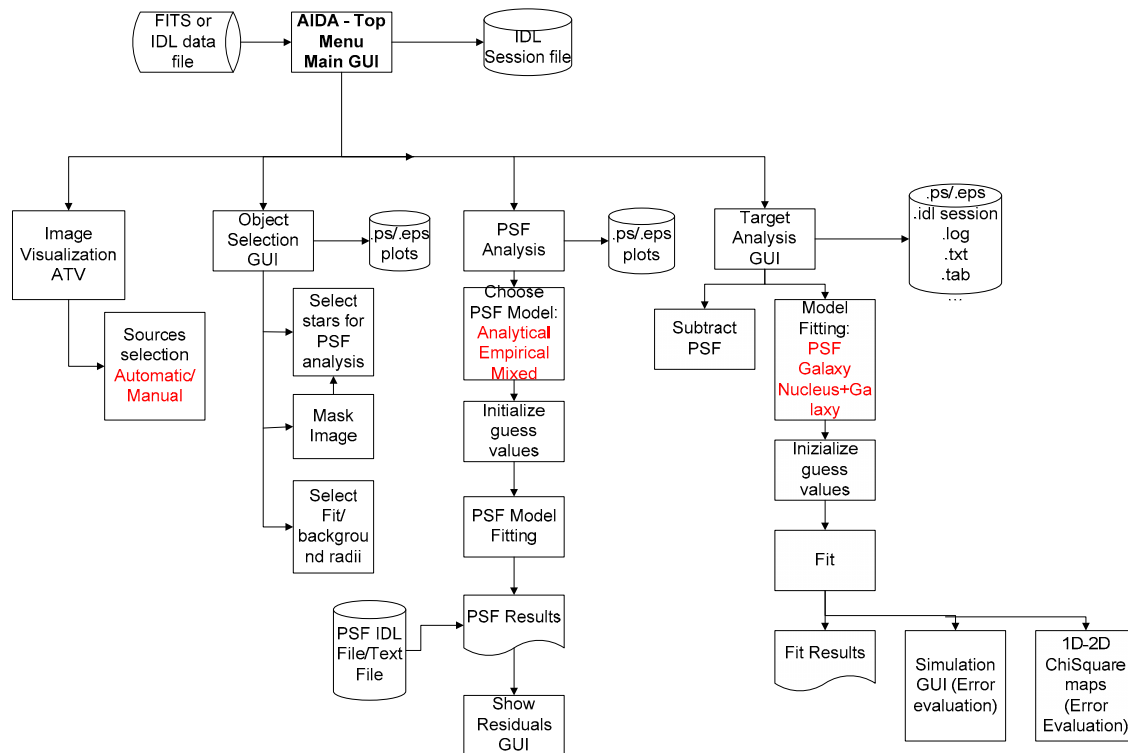- but also allowing the user to customize each step of the analysis, if required

Figure 1 AIDA Block Diagram.

AIDA provides support from the raw image to the object characteristics parameters, through 3 main steps:

1. Sources selection/image preparation
2. PSF model extraction

3. Target model fitting

These 3 steps can be executed all in sequence, or AIDA can be used for only one or two of them. For example, if the PSF is known as a template image, it can be imported in AIDA and step 2 can be bypassed.

A main menu bar is always displayed at the top of the screen, even when the software runs in batch mode. During operations, system messages are displayed in the left area below the menu, assisting the user. At the right side, at any moment, the current status of the analysis session is shown, providing information on the number of stars and targets selected in the image, how many stars have been included in the PSF analysis and if a PSF model is already available.
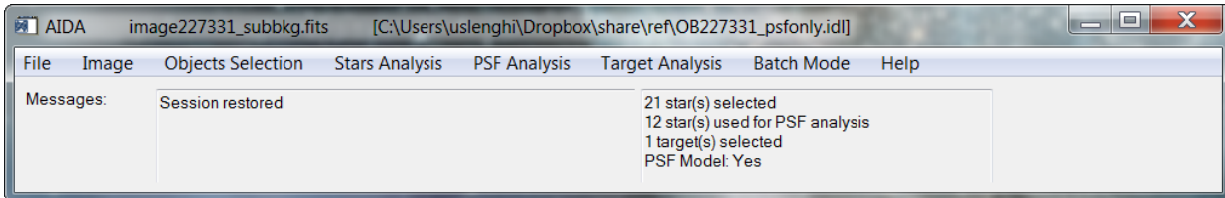

Figure 2 – AIDA Top menu bar. The name of the fits image is showed in the widget title. If the analysis has been restored from a previously saved session, the session file name is also showed. The bottom part is divided in two regions: in the left side the system messages are displayed, the right side at any time gives a short summary of the session in use.
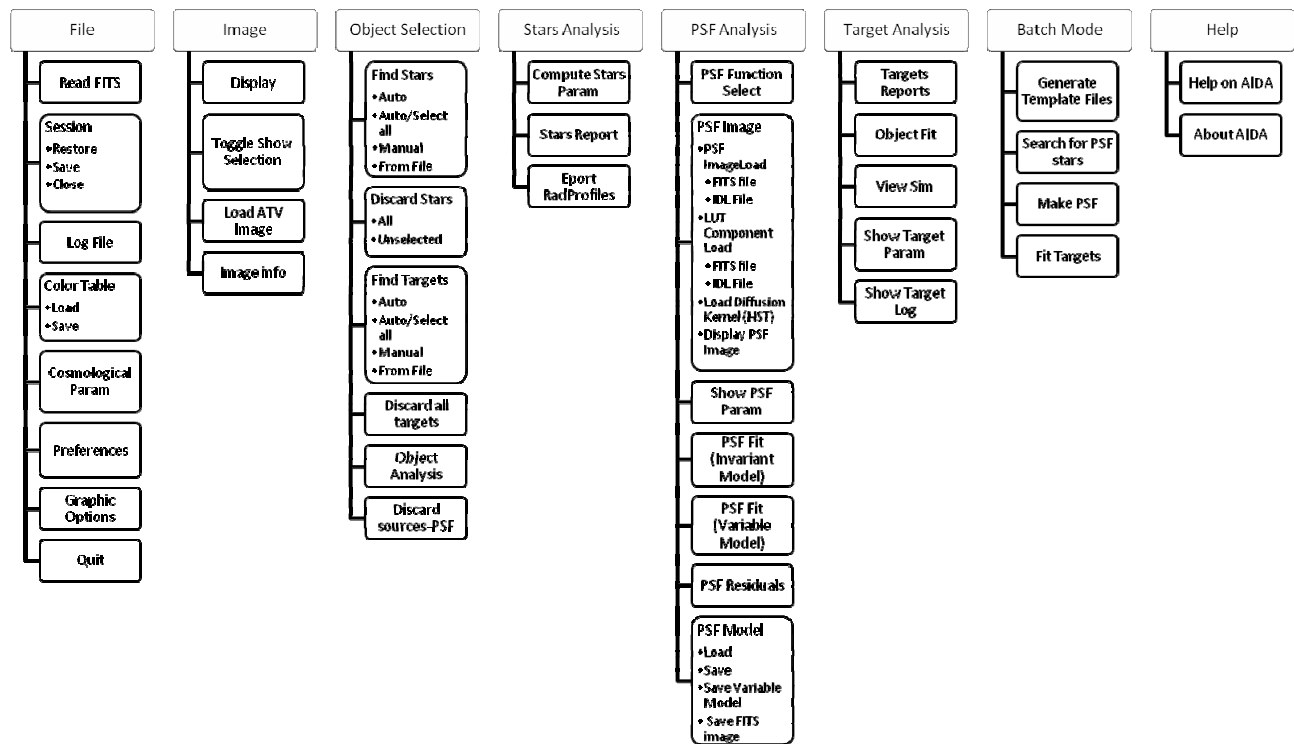

Figure 3 AIDA Menu layout..

Depending on the task, different secondary GUIs are also displayed. At any moment, the overall session of analysis can be saved and restored later. Several formats of output files (from text data files to camera-ready graphic plots) are available.

The user can set several operative parameters through specific forms. The "Preferences" form, which includes the most part of the settings related to the environment, algorithms used and plots appearance is shown in Figure 5.
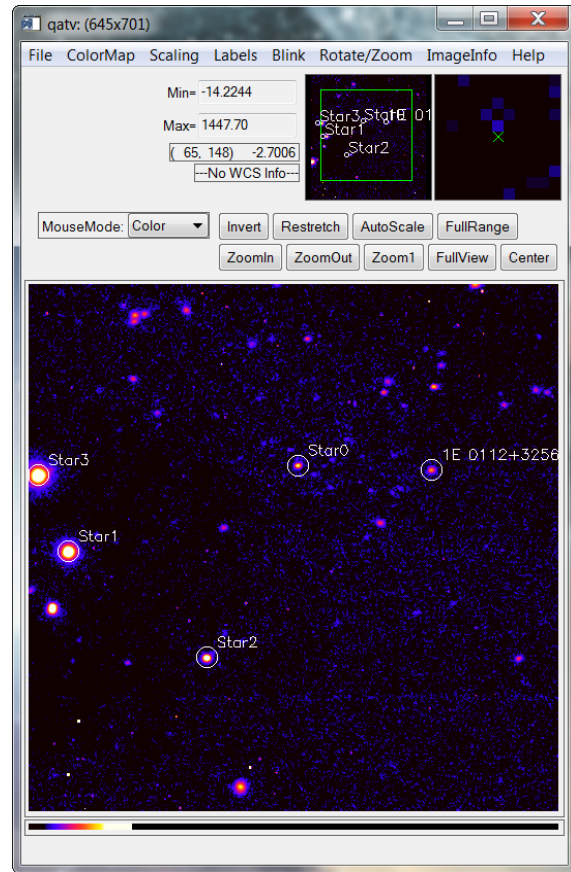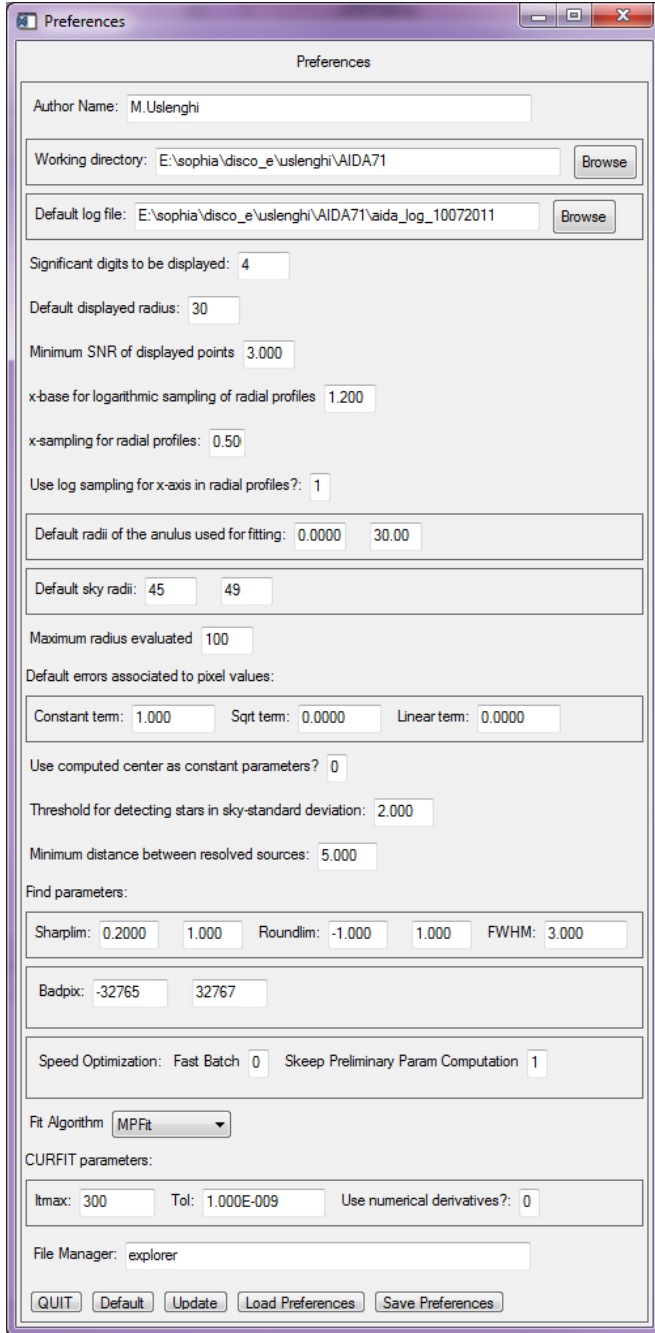
Figure 4 QATV displaying stars and target selected

Figure 5 Preferences form. The user can set several parameters, some are related to the work environment and plot visualization, other allows tuning the algorithms implemented in AIDA.

3. IMAGE PRE-PROCESSING

Image visualization is based on a modified version of ATV[5] which has been integrated in AIDA. ATV is a program written in IDL for display and analysis of astronomical images, with interactive control of the image scaling, color table, color stretch, zoom and point-and-click aperture photometry.

Sources in the images are classified in two groups: "stars", to be used for PSF analysis, and "targets". Other than the manual selection of the sources, two other options are available:

1) Automatic selection: source are selected by the software basing on FWHM, SNR, sharpness, roundness (thresholds and ranges can be modified through the "Preferences" form, see Figure 5)

2) Coordinates from file: if the source positions are known, they can be given as a text file

Once a first selection has been done, a GUI (Figure 6) assists the user in the final choice of the sources and in preparing them for subsequent analysis. For all the sources selected, a preliminary estimate of key parameters like magnitude, FWHM, ellipticity and local background, are displayed, along with a 4-panels visualization of the object (image, contour plot, 3D surface and radial profile). Several interactive controls are available in the right side of the GUI, allowing changing the visualization appearance. Each plot can be exported in an eps file.

For each source, several tasks can be performed:

- mask the image (exclude bad pixels, contamination from other sources and other artifacts)

- define the region to be included in the fit (to exclude saturated or low SNR regions)

- choose the region to be used for computing the local background

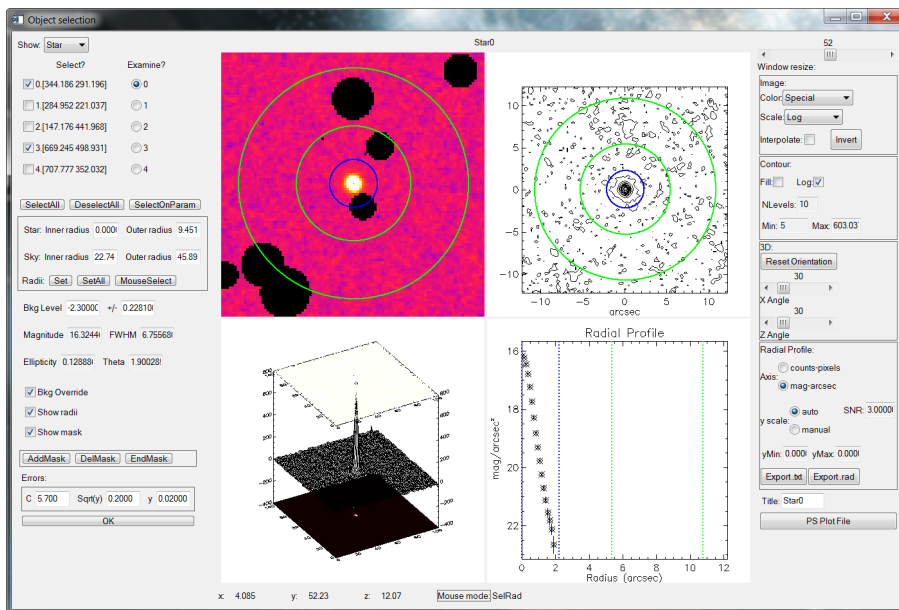Figure 7. Stars selection form based on parameters ranges.

Figure 6. "Object Selection" GUI. The GUI is divided in three part: Left-sources list and their characteristics; Center: graphical visualization, Right: tuning of the graphical appearance of the plots.
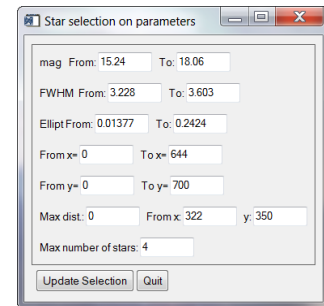
To select the sub-group of stars to be used as reference for PSF modeling, other than choosing stars one, it is possible to provide criteria as range of magnitude, FWHM and ellipticity, or giving constraints on the position of the stars (Figure 7). Moreover, since a common request is selecting stars close to the target to be hereinafter analyzed, in order to characterize the PSF at the target position, the user can provide a maximum distance from a given point of the image. If the number of the stars still meeting the requirements is large, to save computation time a limit on the maximum number of stars can be set. All this can be done filling the form showed in Figure 7.

To help to define the selection criteria, AIDA can produce 3 reports summarizing the characteristics of the stars available:

1) A text table listing the computed parameters for each star

2) A 2d map where stars are represented by bars with length proportional to the ellipticity and orientation equal to the position angle.

3) A postscript graphic report with plots summarizing the distribution of the stars parameters and possible correlations (useful to evaluate the level of the cuts on the parameters)

4. PSF MODELING

The most critical part of the analysis is to perform a detailed and reliable PSF model. PSF can, and generally does, vary over time and with the location in the FoV. Modeling a suitable number of stars in the same image containing the targets, it is possible to characterize space-dependent variation of the PSF and extrapolate the PSF shape at the target location. However, the use of reference stars in the same image of the target is not always feasible (depending on the FoV and on the target field): in this case, stars images taken in conditions as close as possible should be used.

4.1 PSF models

Analytical models have the advantage of being noise-free and can be interpolated at any position. However, empirical models can be more realistic. AIDA can manage various kinds of PSF models: analytical (any combination of provided 2d functions, and user-defined ones can be added) and/or empirical (e.g. TinyTim for HST, or star images).
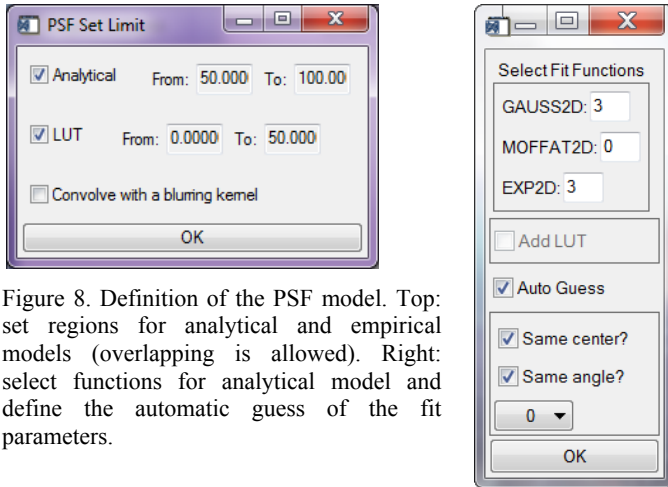

Figure 8. Definition of the PSF model. Top: set regions for analytical and empirical models (overlapping is allowed). Right: select functions for analytical model and define the automatic guess of the fit parameters.

The 2D functions available by default are:

- Gaussian

- Moffat

- Exponential

Empirical PSF can even have a different sampling respect of the image: for TinyTim PSF, in particular, there is support for the convolution kernel, in case an oversampled PSF is provided. Moreover, it is also possible to define 2 different regions with different PSF models (e.g.: empirical in the core and mixed in the wings for HST[6]).

Once defined the kind of model, the parameters are evaluated by minimizing the χ2 defined as:

$$\chi^2 = \sum_x \sum_y \frac{\left(Flux_{x,y} - Model_{x,y}\right)^2}{\sigma_{x,y}^2} Mask_{x,y}$$

"masked" pixels are excluded by the fit.

The weight model is computed defining $\sigma_{x,y}$ as the sum in quadrature of three distinct components with different dependence on the signal level:

$$\sigma_{x,y} = \sqrt{C^2 + \left(SY \cdot \sqrt{Flux_{x,y}}\right)^2 + \left(\alpha \cdot Flux_{x,y}\right)^2}$$

C, SY and α can be provided by the user (through the GUI in Figure 6). If SY= α=0 the fit is unweighted. In general, C describes the constant component of the noise, independent on the signal (in the ideal case it coincides with the "readout noise"); SY describes the component proportional to the square root of the signal ("shot noise", in this case SY is related to the conversion factor $K_{e\text{-}/ADU}$); α represents the "fixed pattern noise".
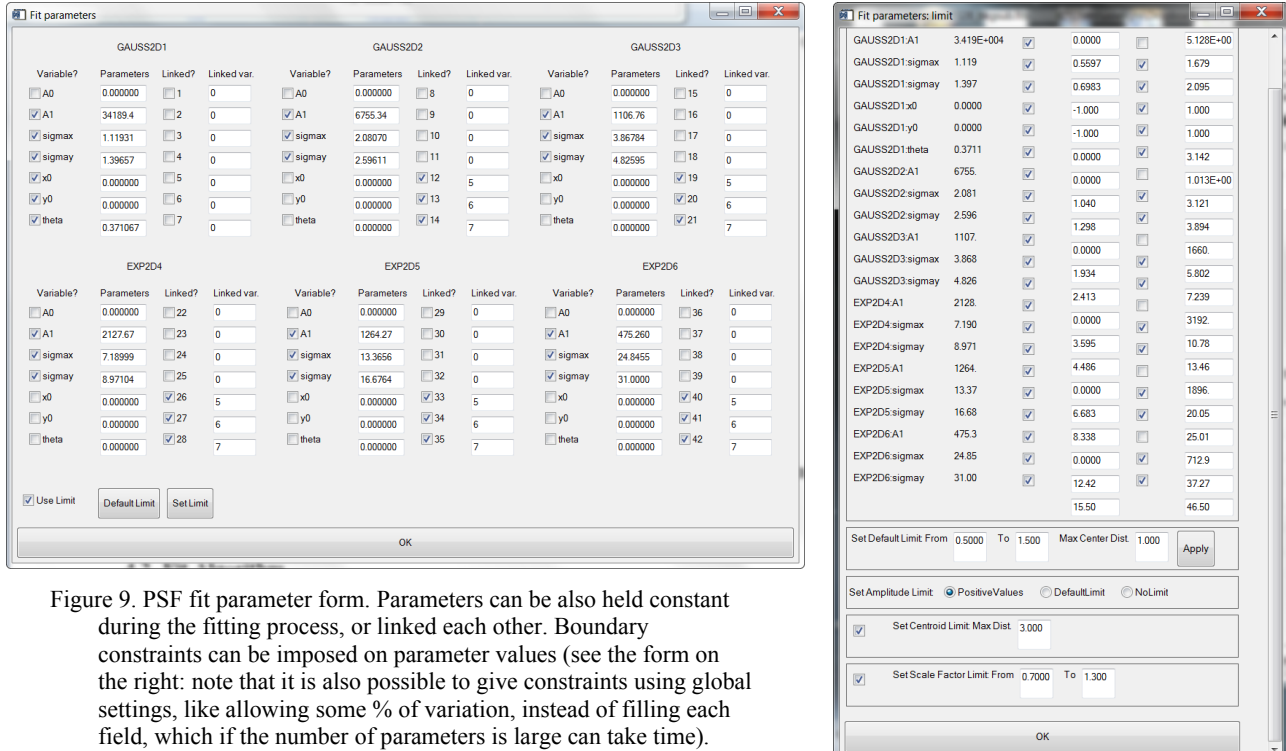
Figure 9. PSF fit parameter form. Parameters can be also held constant during the fitting process, or linked each other. Boundary constraints can be imposed on parameter values (see the form on the right: note that it is also possible to give constraints using global settings, like allowing some % of variation, instead of filling each field, which if the number of parameters is large can take time).

4.2 Fit Algorithms

Two non-linear least squares fitting algorithms are implemented in AIDA and can be selected on the preference form:

- MPFIT, described in [3]

- a modified version of the IDL standard library function CURVEFIT, which uses a gradient-expansion algorithm (based on CURFIT[4]). The original algorithm has been modified in order to allow boundary constraints on the parameters

Generally, MPFIT gives a faster convergence, with less iterations, but sometime the second algorithm can provide a solution even when MPFIT fails.

If a space-invariant PSF is assumed (invariant in the region of the reference stars), it is possible to simultaneously fit the model with the same set of parameters to all the stars. The fit can be done on multiple stars, the maximum numbers being limited by memory resources and computation time. Saturated stars can be used to model the wings (defining the fit area only in the non-saturated region) and less bright stars can be included in the set to model the core. In this case, provided that the data points are enough, complex models with a large number of components (and parameters) can be used and a detailed analytical modeling is possible. If the PSF is slowly changing in the field of view and the field is rich of stars, the approach of choosing reference stars close to the target to be analyzed and assuming the PSF invariant in that region is generally the best since reduce the complexity of the analysis and allows a more detailed modeling.

One of the most critical points for the best fitting concerns the initial guesses for the fit parameters. This can be done by filling the related form. However, if a PSF with many 2-D components is chosen, the number of parameters rises quickly makes unpractical this approach. In alternative the software can provide a reasonable set of initial guesses and constraints automatically, with a multiple step procedure, mainly based on 1-D fitting of the radial profile of the best reference star (preferably not saturated and with high S/N ratio); ellipticity and position angle are instead evaluated by fitting ellipses on isophotes of the faint halo of the star.

The goodness of the fit can be checked by inspecting the residuals, both in 2D or under the form of radial profile.

If the PSF change significantly in the FoV, like in the case of Adaptive Optics instruments, and/or no reference stars are available close to the target, AIDA implements a specific function of individual stars fitting (each star produces a set of

parameters). Using analytical models with a limited number of parameters, and a suitable number of reference stars distributed in the image, dependence of the PSF parameters on the position can be modeled, allowing the interpolation of the PSF model at the target position.

An example of Adaptive Optics PSF evaluated with AIDA is given in [8], based on Ks-band images taken with NAOS-CONICA, the AO system on the VLT at the European Southern Observatory (ESO) in Paranal (Chile).

5. TARGET ANALYSIS

A preliminary analysis on the "target" sources can be done with a simple PSF subtraction, that is useful to give a first look to the object: the target will be subtracted by a PSF normalized to some fraction (chosen by the user) of the flux of the object. The full analysis of the object is performed with 2D model fitting, with three options available:

- PSF
- Galaxy
- PSF+galaxy

Stars can be simply fitted with the local PSF with 3 free parameters: (x,y and flux/magnitude). Galaxy models contain other free parameters such as the scale radius, ellipticity and orientation, and must be convolved with the local PSF (convolution is computed by FFT).

Available galaxy models are:

- De Vaucouleurs
- Disc Law
- Sersic Law

Initial guesses can be computed by the procedure. To minimize the dependency on the initial guesses (which is more an issue in this case than in the PSF modeling, where the fit parameters are not strictly required to have a physical meaning), a procedure can compute the fit with different starting points, randomly extracted in a suitable range.

When the fit is done, a text report is generated with the information of the fit and with the relevant apparent and absolute (if a cosmology is provided) astronomical quantities (magnitudes, radii in kpc or arcsec etc. The goodness of the fit can be checked with the various kinds of plots available in the "Target Analysis" GUI.

Two kinds of visualization are implemented:

- a 3-plots radial profile (see Figure 10) view including:
  - radial profile of the object, best fit model and individual components of the model
  - profile of the residuals of the fit
  - profile of the ChiSquare
- the 4 panels display (image, contour plot, 3D surface and radial profile, like in Figure 6), showing one of the following:
  - object
  - map of the fit residuals
  - best fit model
  - PSF model
  - galaxy model
  - Map of the residuals after subtraction of the PSF only
  - Map of the errors associated to each pixel of the image (used for fit weighting)
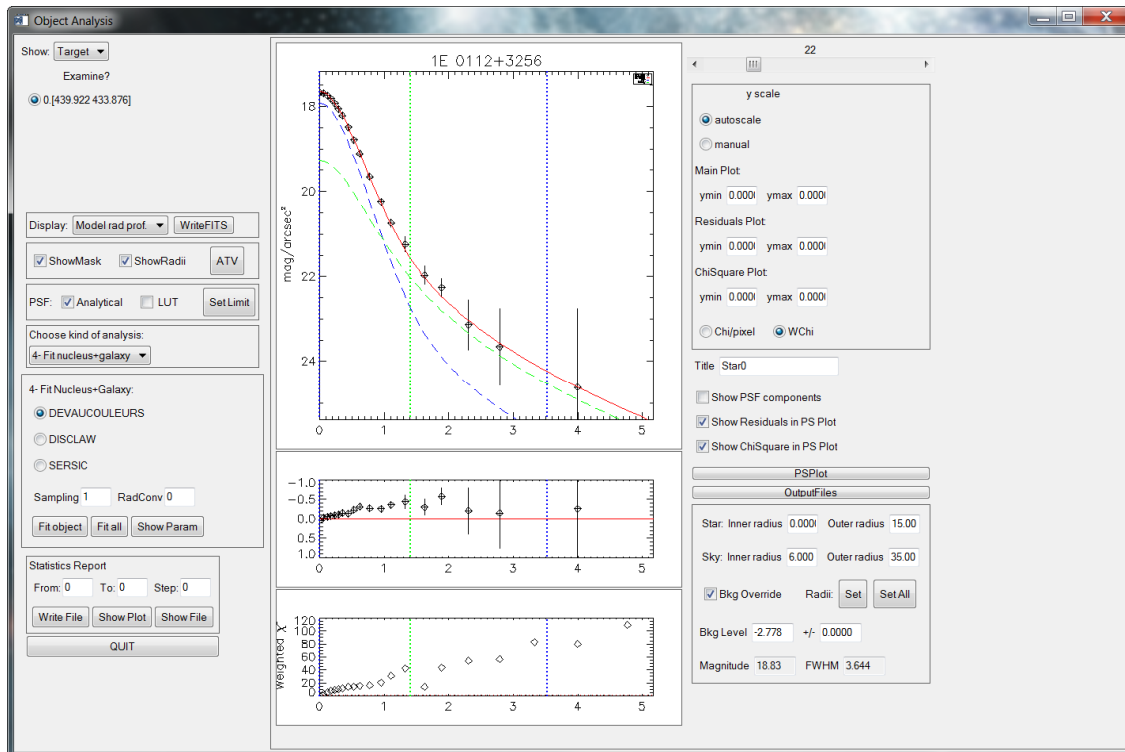 - Map of the χ^2

Figure 10 Target analysis GUI. The structure is similar to the "Object Selection" GUI showed in Figure 6.

Several output products can be generated by AIDA, in several formats. In particular:

- all the plots displayed in the GUIs can be exported in eps files
- all the session variables can be stored in an IDL file
- PSF models can be stored in an IDL file
- text files are generated at each step, summarizing relevant information. Also radial profiles data can be exported in text files
- a PS graphic report can be generated after target model fitting, including relevant plots and results of the analysis
- graphic report of the χ^2 maps, with confidence intervals for the fit parameters
- text report summarizing characteristics of the stars in single /multiple images

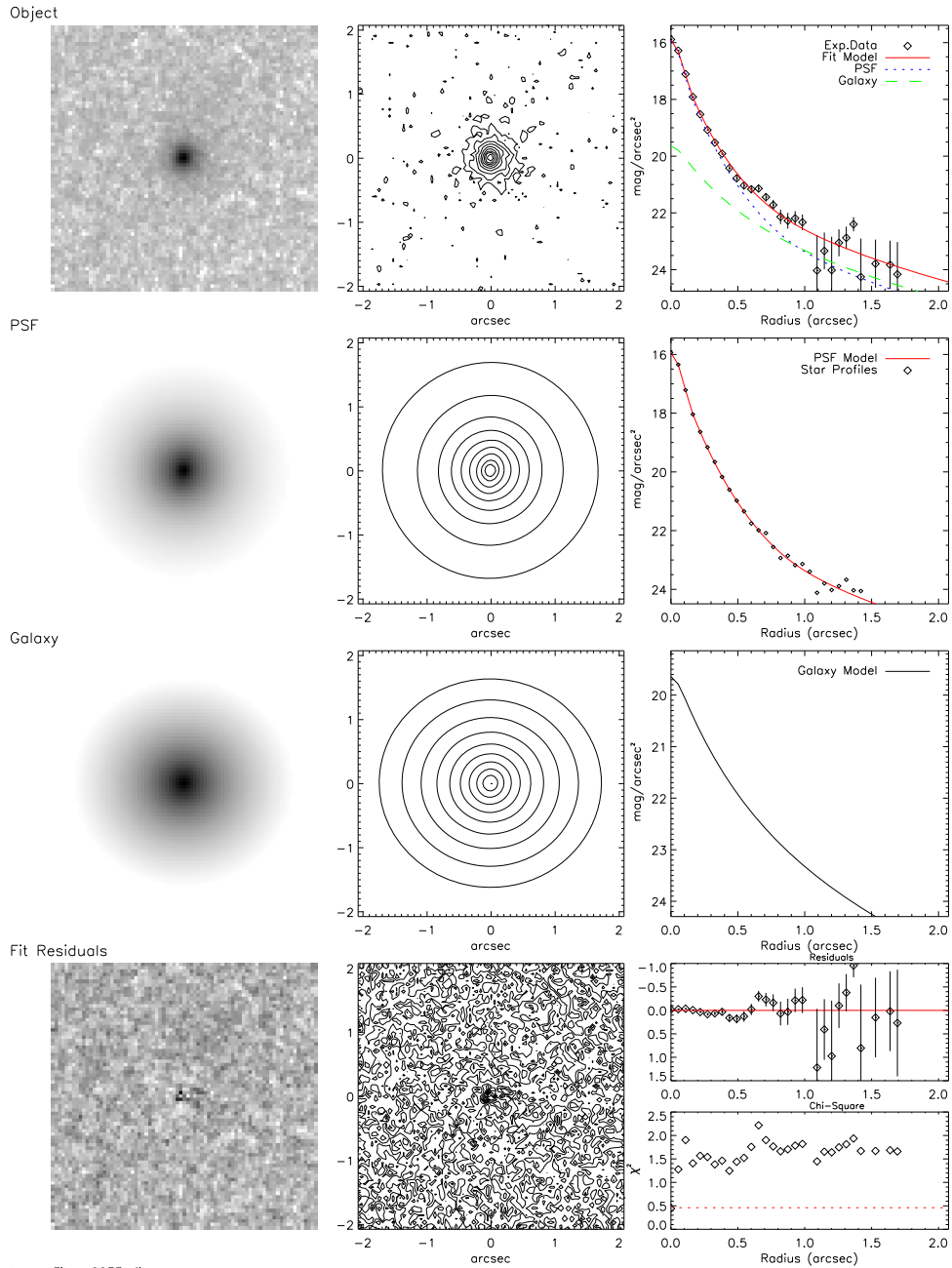Moreover, text tables and plots summarizing results of groups of images can be produced.

Figure 11 Example of the PS graphic report for a QSO after target model fitting, including relevant plots and results of the analysis.

6. AUTOMATIC PROCESSING

When a large number of objects are to be analyzed a fully interactive analysis is unpractical. The "batch mode" of AIDA allows automatic processing of images (PSF modeling & target analysis) providing the list of the (fits) images to be processed. A text configuration file, keyword-based, describes the kind of analysis to apply. The keywords provide good flexibility, allowing the use in automatic of the most part of the features of AIDA. The output files available in AIDA can be generated for each image processed. Moreover summary tables can be produced as well, providing a quick overview of the results of the batch session.

```
# AIDA template psf used for aida batch : make PSF
#
#  Version : 2011 June 20
#
FPATH=/home/user/data/test/
#
# List of input images
INPUT_FILES = list_files.dat
#
# List of files that are processed
OUTPUT_FILES = list_file_psf.dat
#
# List of PSF files corresponding to that in OUTPUT_FILES
PSFINDEX_IDL_FILES = list_idlpsf.dat
#
# List of
PSFINDEX_FITS_FILES = list_fitspsf.dat
#
INDEX_IDL_FILES = index_sessions_idl.dat
#
ERROR_LOG = AIDA_makepsf_error.log
#
# Mask the image, if USE_MASK=1 and files *.msk are found
(default=1)
#
USE_MASK = 1
#
#
# Maximum number of files of the INPUT_FILES list to be
analyzed
# (if -1 -> analyze all the files)
#
MAX_NFILES = -1
#
#
FDIM_MAX = 30
#
# set weight parameters for fitting
#
W_C=1
W_SQRTY=0
W_Y=0
#
FIT_ALG=1
NODERIVATIVE=0
#
# PSF_KIND: 0 = analytical, 1 = LUT, 2 = analytical & LUT
#
PSF_KIND=0
ADD_LUT=0
#
# REFINE_POSITION: 0-> use the exact coordinates given in
'.cos' file
REFINE_POSITION = 10
#
N_FUNC_GAUSS = 3
N_FUNC_MOFFAT = 0
N_FUNC_EXP = 1
#
NREPEAT=3
#
# Set output files: 0 = no ; 1 = yes ;
#
OUTFILE_IDL = 1
OUTFILE_PSF_IDL = 1
OUTFILE_PSF_FITS = 1
OUTFILE_CHI_TAB = 1
#
# Output in FITS of individual sources
#
OUTFILE_SRC_OBJECT = 0
OUTFILE_SRC_RESMAP = 0
OUTFILE_SRC_ERRMAP = 0
OUTFILE_SRC_CHIMAP = 0
OUTFILE_SRC_PSF =  0
OUTFILE_SRC_RESIDPROF = 1
#
```

```
# AIDA template file for targets
#
# Version: 2011 July 26
# ------------------------------------------------------------
--
#
# Format is: KEYWORD = <value> ; if boolean 0=NO, 1=yes
#
#
# Choose the kind of analysis for the objects
#
# SUBPSF = subtract best psf from object        : A0
# FITPSF = fit best psf to the object           : A1
# FITGAL = fit best galaxy to the object        : A2
# FITPSF = fit best galaxy+psf to the object    : A3
#
# Select type of analysis:
#
ANALYSIS_SUBPSF = 0
ANALYSIS_FITPSF = 0
ANALYSIS_FITGAL = 0
ANALYSIS_FITNUCGAL = 1
#
# Choose the model (function) for the galaxy
#
# DEVAUC  : F0
# DISCLAW : F1
# SERSIC  : F2
#
TARGET_FUNC_DEVAUC = 0
TARGET_FUNC_DISCLAW = 0
TARGET_FUNC_SERSIC = 1
#
SAMPLE = 1
#
RAD_CONV = 0
FDIM_MAX = 100
#
# Write the path of the data
#
FPATH = /home/aida/data/
# file containing the list of images (.fits)
#
INPUT_FILES = object_list.dat
#
# Mask the image, if USE_MASK=1 and files *.msk are found
(default=1)
#
USE_MASK = 1
#
# Maximum number of files of the INPUT_FILES list to be analyzed
# (if -1 -> analyze all the files)
#
MAX_NFILES = -1
#
# file containing the list of psf images OR
# the name of one PSF in fits is the same is used
#
PSF_FILE = psf_list.dat
#
# file containing the list of idl sessions produced
#
INDEX_IDL_FILES=index_session_idl_tgt.dat
#
# Log file for errors
#
ERROR_LOG = AIDA_target_error.log
#
NREPEAT = 3
# REFINE_POSITION: 0-> use the exact coordinates given in '.cot'
file
REFINE_POSITION = 5
#
W_C = 1
W_SQRTY = 0
W_Y = 0
#
FIT_ALG = 1
```

```
#
#
# set output files: 0 = no ; 1 = yes ;
#
OUTFILE_IDL = 1
OUTFILE_TAB = 1
OUTFILE_PS  = 0
OUTFILE_RAD = 0
OUTFILE_RES = 0
OUTFILE_TXT = 0
OUTFILE_PSF = 0
OUTFILE_LOG = 0
OUTFILE_CHI_TAB = 1
#
#
# Output in FITS of individual sources
#
OUTFILE_SRC_OBJECT = 0
OUTFILE_SRC_RESMAP = 0
OUTFILE_SRC_ERRMAP = 0
OUTFILE_SRC_CHIMAP = 0
OUTFILE_SRC_PSF = 0
OUTFILE_SRC_GALAXY = 0
OUTFILE_SRC_OBJSUBPSF = 0
OUTFILE_SRC_RADPROF = 1
#
# RADPROF_MAXR = 0 -> xrange of the radial profile=0,star_rad
#                1 -> xrange of the radial profile=0,sky_rad1
#                2 -> xrange of the radial profile=0,sky_rad2
#
RADPROF_MAXR = 2
```

Figure 12 Templates of the configuration files for batch processing. Left: PSF modeling, Right: target analysis.

7. CONCLUSIONS

We developed AIDA, an user friendly software for 2D analysis of astronomical images. AIDA can manage complex PSF models, including characterization of its spatial variability and can work in "interactive" mode & in "batch" mode. It was been used to analyze data from different instruments, including AO images complex and variable PSF. Examples of analysis carried out with AIDA can be found in [6-12].

AIDA is freely distributed (at the moment only in binary code) upon request to the author (uslenghi@iasf-milano.inaf.it) or at the URL http://aida.iasf-milano.inaf.it/.

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