# Modern Image Processing Techniques in Astronomical Sky Surveys

*Items of the PhD thesis*

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# Introduction

Astronomy nowadays, like other fields of science, increasingly relies on automated data processing methods, which made possible the creation of recent large-scale sky surveys. We need sophisticated image processing software in order to extract useful data from the observations.

In this work I present advanced image processing methods to measure various properties of astronomical sources, such as brightness, distance, size, shape etc.

It is the scope of my thesis to develop new software tools to determine shapes of galaxies and to detect faint sources, while fixing several issues present in some current algorithms. By applying my methods to real astronomical data I am trying to uncover some previously hidden phenomena that can help us to learn more about the evolution and nuclear activity of galaxies.

Reliable shape and position angle measurements of galaxies are essential for a number of fields of extragalactic astronomy including the investigation of correlations between the orientation and spatial distribution of galaxies (*intrinsic alignments*) or the weak gravitational lensing effect caused by the cosmic superstructures (*cosmic shear*). These observations help us to study the large-scale distribution of dark matter, the formation of galaxies and the interaction between galaxies and the dark matter.

More than half of the sources identified by recent radio sky surveys have not been detected by wide-field optical surveys. The nature of the optically undetected fraction has been the subject of debate for many years. Recent studies have shown that there exists a significant population of reddened quasars, which are often missed by the conservative quasar selection criteria of optical sky surveys. These *dust-reddened* quasars represent an early phase in the evolution of the active galaxies. In this phase, the active galactic nucleus has high intrinsic luminosity, but it is heavily obscured by the surrounding dust. The radio emitting relativistic jets coming from the nucleus extend so far away, that they are not affected by the obscuring dust.

## Methods

Digital sky surveys are capable to detect millions of astronomical sources automatically. Photographs of the sky are taken with CCD detectors and processed by computer software. It is very important to have reliable automatic measurements on the brightness, shape, redshift, etc. of stars and galaxies.

My first topic is the analysis of position angles and orientations of galaxies. In case of spiral galaxies we can see a projected image of the galactic disk, which is usually an ellipse. By measuring the position angle and axis ratio (ellipticity) of the ellipse the orientation of the galaxy can be obtained. I have studied the distribution of galaxy position angles from the SDSS catalogue using histogram plots.

The second topic is the detection and photometry of faint sources. *Co-adding* repeated observations and *stacking* of images of different, but similar objects can be used to extend the limiting magnitude and surface brightness limits of surveys. For undetected sources, stacking can be successfully used to reveal an average image of extremely faint sources that otherwise would be beyond the detection limits of the instruments. The individual objects must be similar to each other in order to be able to give a physical interpretation to the average images. Image stacking is a useful tool in multiwavelength studies, when objects are detected in a specific wavelength range, but not in an other.

The data of sky surveys are published in catalogues, many of them are freely accessible on the World Wide Web. The catalogues of the optical Sloan Digital Sky Survey (SDSS) are managed in a relational database management system. Data from the SDSS catalogues can be retrieved by standard SQL queries.

The SDSS Stripe 82 (S82) is a $\sim 300°$ region of sky that was imaged multiple times by the SDSS telescope. The images were then co-added from 20–40 individual exposures, and a deeper catalogue was created by processing the co-added images. In this work I have made extensive use of the S82 survey data: the photometric catalogue, and the co-added science images as well. I have developed my own image processing software tools in IDL.

## Items of the PhD thesis

1. I have found a strong systematic bias in the distribution of the SDSS model fitted ellipticities and position angles. I have concluded that the bias is mainly caused by the binning of the radial profiles of the objects into 30° sectors around the object centroids, and the failure of the $\chi^2$ minimization algorithm of the fitting procedure [2].

2. I have developed a reliable algorithm which determines position angles and ellipticities by the means of isophote fitting. This method is free from the bias present in the SDSS processing pipeline. I have reprocessed the SDSS S82 co-added images with my technique, and compiled a catalogue of 26397 spectroscopically confirmed galaxies containing new position angle and ellipticity measurements [2].

    - The new algorithm fits an ellipse to the isophote (contour line) of a given surface brightness level, and it returns the minor axis, major axis and position angle of the fitted ellipse.
    - The catalogue of galaxy orientations contains the new shape parameters and other data (e.g. optical magnitudes, redshift) from the S82 co-added catalogue.

3. I have developed an image stacking algorithm with an efficient masking technique to recover the undetected light from objects that are visible in a given wavelength range but are too faint in an other to detect them directly [1].

    - I have selected a sample of 2116 objects, divided into three subsamples, from the FIRST radio survey that have no identified optical counterparts in the SDSS S82 co-added data set (*stack sample*).
    - I have developed an image processing utility specially designed for the photometry of faint or stacked sources, with an elaborate background subtraction technique.
    - I have demonstrated the robustness of my stacking algorithm by applying several statistical tests, including jackknife resampling, histogram analysis and by varying the masking parameters.

4. I have stacked S82 co-added optical images centred on the FIRST coordinates, and I were able to detect the faint average optical emission of the radio-selected sources (*stacked object*). I have investigated the optical properties of the stacked objects, and concluded that the majority of the radio-selected sources are dust-reddened Type 1 quasars [1].

    - The stacked objects have $r \approx 24{,}7$ mag, which is $\sim 1$ magnitude fainter than the limiting magnitude of the S82 co-added survey. The colours of the stacked objects imply a steep, red optical spectrum with spectral indices of $-2.9 \leq \alpha_\nu \leq -2.2$.
    - I have created a radio-selected sample with faint optical detections in the S82 co-added catalogue (*cross-check sample*), similar to the stack sample. I have compiled a catalogue

of the optical, infrared and radio properties of the cross-check sample. The cross-check sources are detected in the co-added catalogue, but not in the SDSS single pass data.

- I have compared the optical and near infrared colour indices of the stacked and the cross-check objects with various spectroscopically identified quasar samples. I have found that the distribution of the colours imply that the majority of our radio-selected sources are indeed dust-reddened Type 1 quasars.

# Conclusion

The SDSS position angle data are widely used in the scientific community. The inaccurate or biased shape measurements cause significant contamination to the generally very weak correlation signal of the intrinsic galaxy alignments. In the future more elaborate shape measuring image processing tools are required, which can robustly model the effect of the seeing and the optical distortions of the telescopes.

In agreement with other authors I have found evidence for the existence of a red quasar population with an image stacking analysis of FIRST radio sources. Reddened quasars are often missed by the conservative quasar selection criteria of optical sky surveys. I assume that the forthcoming optical and infrared survey telescopes might discover many more obscured quasars than previously expected.

# Publications

[1] **Varga, J.**, Csabai, I., & Dobos, L. (2012): Revealing a strongly reddened, faint active galactic nucleus population by stacking deep co-added images. *Monthly Notices of the Royal Astronomical Society*, **426**, 833–850

[2] **Varga, J.**, Csabai, I., & Dobos, L. (2013): Refined position angle measurements for galaxies of the SDSS Stripe 82 co-added dataset. *Astronomische Nachrichten*, **334**, No. 9, 1016–1019

# Conferences

[3] **Varga, J.**, Csabai, I., & Dobos, L. (2012): Revealing a strongly reddened, faint AGN population with double image stacking. *International Astronomical Union XXVIII General Assembly*, (Beijing, China), August 2012 (poster)

[4] **Varga, J.**, & Csabai, I.,(2012): Morphological analysis of SDSS disc galaxies. *$6^{th}$ Workshop of Young Researchers in Astronomy and Astrophysics*, (Budapest, Hungary), September 2012 (talk)

[5] **Varga, J.**, Csabai, I., & Dobos, L. (2013): Correct measurements of galaxy orientation angles and its implications to angular correlation studies. *Ripples in the Cosmos* (Durham, United Kingdom), July 2013 (poster)

[6] **Varga, J.**, Csabai, I. (2014): Intrinsic alignment between galaxies and the large scale structure. *Alpine Cosmology Workshop 2014* (Gschnitztal, Austria), July 2014 (abstract submitted, talk)