Probing the Properties of Elliptical Galaxy Cores: Analysis of High Angular Resolution Data

W. W. ZEILINGER[1], P. MØLLER[2] and M. STIAVELLI[3]

[1]ST-ECF, Garching, Germany: [2]ESA STScI Baltimore, Md, U.S.A., [3]Scuola Normale Superiore, Pisa, Italy

Introduction

The cores of elliptical galaxies provide important clues to the formation and dynamical evolution of the parent galaxies, e.g. recent episodes of star formation, merging and cannibalism and possible presence of black holes. Many "features" are observed in the central region of ellipticals: Cores kinematically decoupled from the main body of the galaxy are known to exist in many ellipticals and are widely interpreted as evidence for galactic cannibalism. However, different signatures of the decoupling have been found which may not necessarily be related to each other: central light excess (Kormendy 1985), kinematically decoupled cores, i.e. misalignment of the angular momentum vectors of the stellar component in the central region with respect to the main galaxy body, and finally core radio sources and X-ray emission found in ellipticals may indicate the presence of a (super) massive central object. More recently, unresolved nuclei have been discovered in many ellipticals and seem to be a much more common phenomenon than previously thought as also pointed out by the HST observations of the core of the early-type galaxy NGC 7457 (Lauer et al. 1991). Crane et al. (1993) reported central mass densities in excess of 10^3 $M_\odot/pc^3$ for several galaxies.

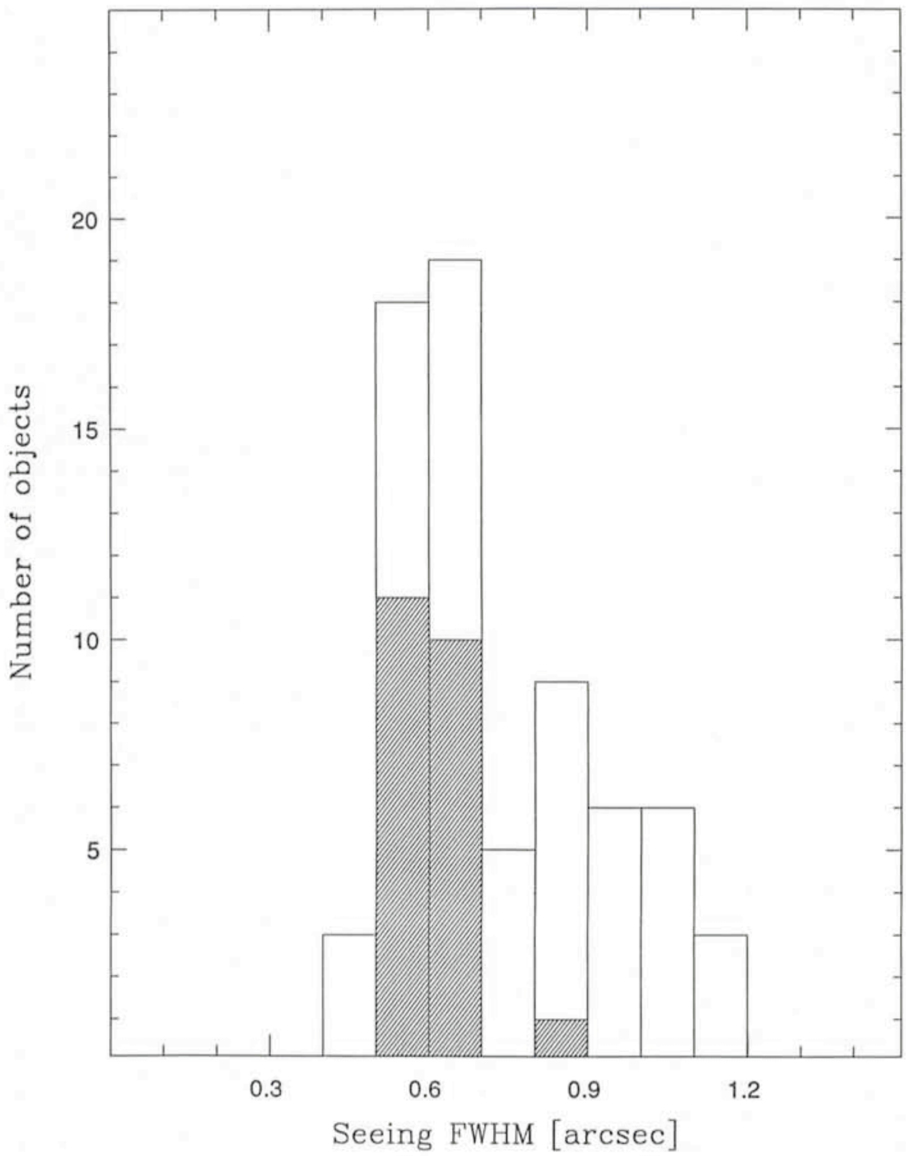

Figure 1: *Distribution of best seeing values of a sample of 69 galaxies. The shaded area indicates objects observed at the NOT. The remaining data are from the NTT using SUSI.*

Despite the fact that a wide range of core properties has been found in elliptical galaxies, no homogeneous survey has been carried out so far with the necessary high resolution. Therefore, nature and physical interpretation of galaxy cores are still subjects of discussion. The largest sample published so far is the compilation by Lauer (1985) of surface photometry for the cores of 42 early-type galaxies. Lauer's sample, however, is not complete and based on single waveband observations carried out at a 1-m telescope with a medium seeing of about 1.7 arcsec FWHM and no comparable kinematic survey exists in the literature.

The Survey

On the basis of the morphological classifications in the "Catalogue of Principal Galaxies" (Paturel et al. 1989) and the "Third Reference Catalogue of Bright Galaxies" (de Vaucouleurs et al. 1991) all elliptical galaxies within a redshift of 3000 km/s were selected for the present survey, in total about 230 galaxies. The aim of the survey is to obtain a homogeneous set of high-resolution multi-colour surface photometry data and major-axis long-slit spectra for the whole sample. As a first step VRI images were obtained at the 2.5-m Nordic Telescope (NOT) for the northern hemisphere and at the ESO 3.5-m NTT using the direct imaging facility SUSI for southern hemisphere objects. In addition, using the ESO Archive Database facility within STARCAT, the NTT data archive was systematically searched for adequate galaxy images. Long-slit spectra for southern hemisphere objects were obtained using the ESO 1.5-m telescope during several observing runs. For a sub-sample of objects, images and spectra were obtained at the ESO/MPI 2.2-m equipped with EFOSC2 and IRAC2 and also at the NTT with EMMI. The long-slit spectra should provide information on global kinematic properties on the (ionized) gas and stars and identify candidates for high-resolution studies.

Most of the effort so far has been put in performing surface photometry and further analysis of the images. The resolution of the NOT and NTT-SUSI data are of comparable order. The respective scales on the detector are 0.20 and 0.13 arcsec/pixel. In Figure 1 the best-seeing values for 69 galaxies are presented which have been analysed so far from the VRI data sample. The seeing was measured on stellar-like images in the respective frames. A data base of images obtained at very good (exceptional) seeing conditions is an essential ingredient for this project. However, in order to take full advantage of the high-resolution data one needs also take into account effects of seeing, telescope guiding, etc. which affect the image quality. Some experiences on handling and analysing such images are presented in the following sections.

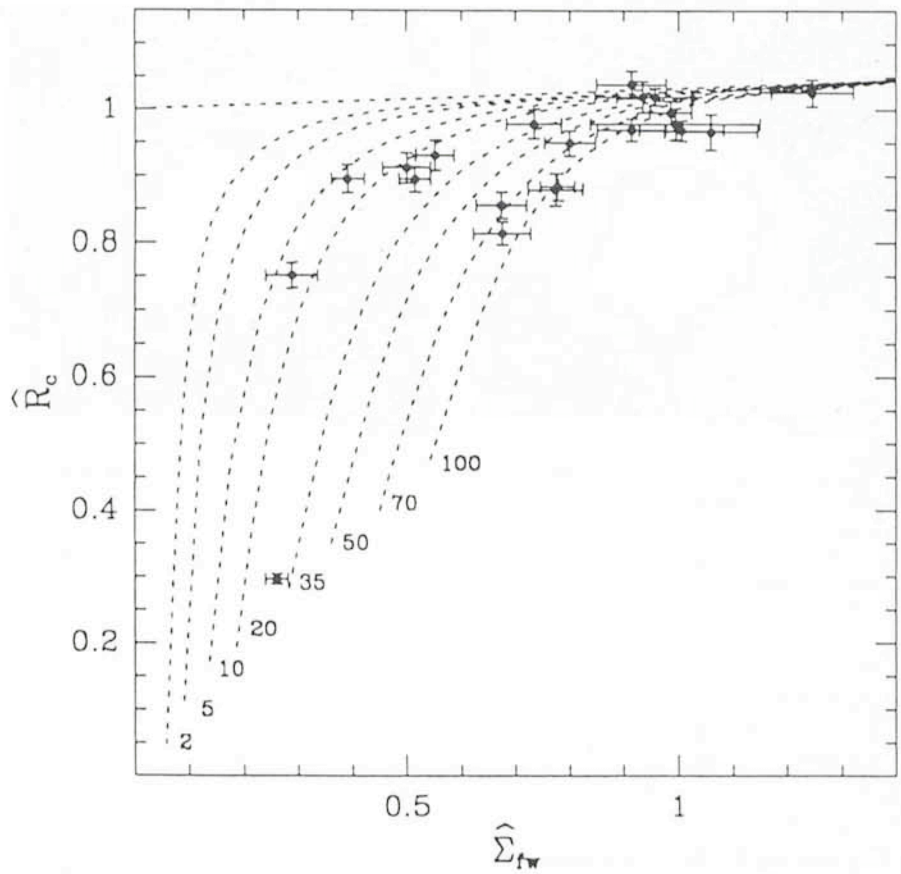

Figure 2: *Core resolution diagram for a sample of 21 galaxies observed at the NOT. The galaxy data are plotted with 1σ error bars. The uppermost dotted line indicates the location of isothermal cores. The other dotted curves represent non-isothermal cores with their respective spikyness π_c. The units of π_c are parts per thousand of the underlying core flux. Resolved cores will lie in the left part of the diagram, unresolved ones in the right part.*

Parametrization of the (Photometric) Core Properties

The "classical" galaxy core parameters are the central surface brightness and the core radius (i.e. radius of the isophote at which the surface brightness has decreased by a factor of two with respect to the central surface brightness). It is immediately evident that these parameters depend crucially on the seeing conditions during the observations, and several studies have addressed the problem of how to consistently correct the parameters for these seeing effects. The most commonly used methods of seeing correction have been to firstly extract the luminosity profile of the galaxy, and then either (i) deconvolve the profile directly with an appropriate PSF (Lauer 1985, (ii) measure the core parameters of the extracted luminosity profile and apply seeing corrections found by convolution of core models with a PSF (Kormendy 1985), or (iii) use directly the core parameters derived from galaxy models fitted to the luminosity profile (Kormendy & Richstone 1992). It is evident that these methods all have their limitations: As shown by Møller, Stiavelli & Zeilinger (1992a, 1992b), deconvolution of luminosity profiles cannot in general compensate for lack of resolution (like bad seeing) and seeing corrections using light profiles derived from galaxy models are necessarily model-dependent (i.e. one has to know in advance properties and structure of the core and the underlying galaxy, to be able to determine them).

In order to reduce the seeing dependence of the classical core parameters we have introduced a new type of core radius, which for an isothermal (Hubble law) core is identical to the classical core radius but which does not depend strongly on the core structure (e.g. presence of a central point source). The Petrosian core radius (Petrosian 1976), which is defined as the distance from the centre at which the local surface brightness has fallen to some fraction of the *mean* surface brightness inside that radius, will reduce the influence of the seeing since it depends only on the total flux inside the radius irrespective of its distribution. Two core resolution parameters were introduced in order to quantify the observed core properties, namely $\hat{\Sigma}_{fw}$ = seeing FWHM/R_n and $\hat{R}_c = R_c/R_n$ with R_c being the observed core radius and R_n the Petrosian radius as previously defined. *$\hat{R}_c$ is an isothermality measure, i.e. for an isothermal core $\hat{R}_c$ = 1*, while $\hat{\Sigma}_{fw}$ represents an inverse resolution measure, $\hat{\Sigma}_{fw}$ = 0 indicates a fully resolved core and becomes larger when the same core is observed with worse seeing. The $\hat{\Sigma}_{fw}$ versus $\hat{R}_c$ plane (core resolution diagram is therefore a useful tool for the first direct analysis of the observed data and their quality. As a first step of analysing the single galaxy data and their location in the core resolution diagram, one may quantify the non-isothermality of the core in terms of "equivalent point-source flux-fraction" (spikyness parameter π_c). Such an example is shown in Figure 2 using a sub-sample of 21 galaxies observed at the NOT. As a next step one may apply analytical models using parametrized central point sources, power laws or central cusps introduced by a black hole to interpret the data. Such a study has been carried out for the elliptical NGC 1399 (Stiavelli, Møller & Zeilinger 1993).

A more detailed introduction to the core resolution technique together with

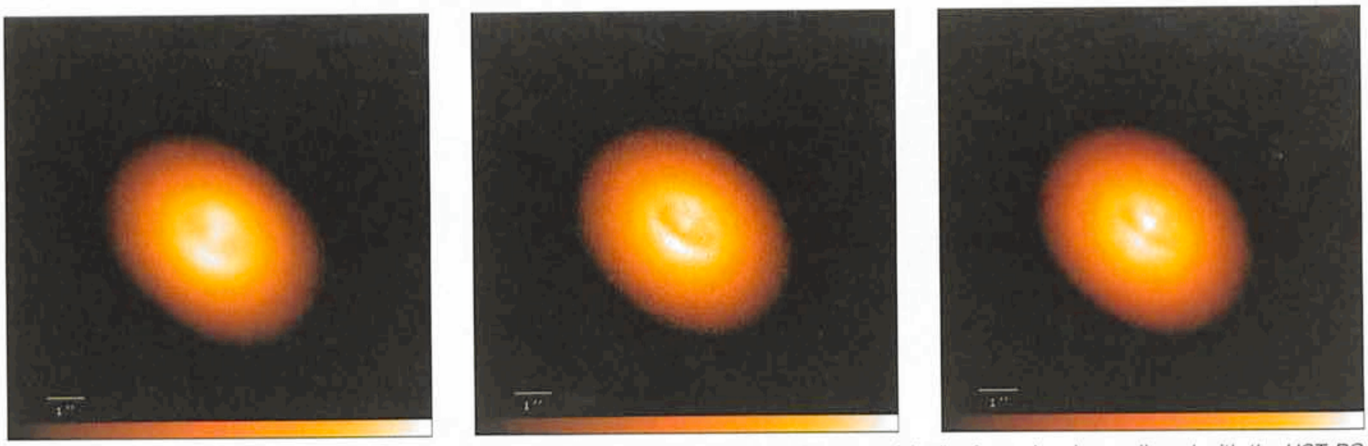

Figure 3: *(a) R band image of NGC 4261 obtained with NTT-SUSI (exposure time 120 seconds). The frame has been aligned with the HST-PC image and rebinned to the PC detector scale. The seeing FWHM is 0.63 arcsec.*
(b) F555W band HST-PC image of NGC 4261 (exposure time 1700 seconds). The image is rotated 68° counter-clockwise with respect to the astronomical convention.
(c) Combined SUSI and PC image using the co-addition technique after applying 150 iterations of the Richardson-Lucy restauration algorithm. (See also the article on page 37 of this issue.)

a presentation of the first scientific results and implications is given by Møller, Stiavelli & Zeilinger (1992a, 1992b).

The Search for Sub-Components in the Nuclear Region

The use of image restoration techniques becomes more and more popular not only in relation with HST data. One of the most versatile tools is the Richardson-Lucy technique whose algorithm is now part of major image processing packages like IRAF and MIDAS. The straightforward application of this algorithm enables the correction of earlier mentioned impairments of the image quality by means of an appropriate PSF and allows enhancements of faint structures. The study of the nuclear gas and dust disk in NGC 3557 is such an example (Zeilinger, Stiavelli & Møller 1993).

An interesting option of the method is the possibility to combine images having different PSFs (resolutions). The co-adding technique, using the Richardson-Lucy algorithm, consolidates the signal of different images but conserves the resolution of the sharpest one. A more detailed description of the method is given by Lucy (1991) and Hook & Lucy (1992). One is now in the position to take full advantage of the high-resolution images in the HST Data Archive, by co-adding them with (high signal-to-noise) ground-based data. In order to illustrate the capabilities of this method the well-known elliptical NGC 4261 (Ford et al. 1993) has been chosen. The core region of this galaxy is characterized by a dust lane (radial extent less than 2 arcsec) and a point source. Figure 3a shows an NTT image of NGC 4261 obtained with SUSI (detector scale 0.13 arcsec/pixel). From star-like images a seeing FWHM of 0.63 arcsec was determined. An HST Planetary Camera (PC) image of NGC 4261 (detector scale 0.0439 arcsec/pixel) is shown in Figure 3b as comparison. The frame was extracted from the HST Data Archive. The SUSI image was rebinned to the scale and then aligned with the PC frame. Because of missing field stars, the alignment of the two images was done using the (bright) galaxy nucleus as reference point. Therefore the accuracy of the alignment of the two images is only at the level of 1 (PC) pixel. The selection of the "right" PSF is a crucial part for the image restauration and subsequent co-addition. A well-exposed star within the frame was used for the SUSI image of NGC 4261. In the case of the PC image the situation is much more difficult. Given the fact, that the shape of the PSF varies as a function of the location in the frame, one needs to know the PSF in position of the observed object. Useful stellar images, repeating the exact instrument configuration, are therefore almost never available. A solution to this problem gives the software tool TINYTIM (Kirst 1992) which can calculate an "artificial" PSF for a given observation date and instrument configuration. The usage of the package is straightforward, however, one has to be aware that TINYTIM is only a tool based on current best fits of aberration values for the various mirror positions and current best estimates of the obscuration positions and sizes which may still not describe the HST PSF *exactly*. After applying 150 iterations the deconvolved image was convolved again with the appropriate PSF. The result is shown in Figure 3c. The resolution of the PC image has been retained, shape and structure of the central dust lane profit however from the better signal-to-noise ratio of the ground-based image.

In the context of studying core regions of elliptical galaxies at high spatial resolution, one of the main open issues is the question of the (non) presence of central black holes. There have been extensive studies in this field (e.g. Kormendy 1993, Nieto 1992) pointing out, however, mostly circumstantial evidence like (radio) jets, compact (unresolved) radio sources or core fluxes in excess of an isothermal galaxy core. The nearby elliptical NGC 4486 (M87) illustrates very well the problem (Zeilinger, Møller & Stiavelli 1993). Despite its obvious signatures of nuclear activity and non-isothermal core, it was up to now not possible to pinpoint the nature of the central source. The kinematics in the nucleus is a key element in this study. It is by now a well-established fact that, in general, giant (high-luminosity) ellipticals are not rotationally flattened systems. Therefore, in order to account for their triaxial shape, they must have an anisotropic velocity distribution. It has been shown that most of the light contribution in excess of an isothermal model can be explained by an even modest anisotropy in the velocity field (Binney & Mamon 1982). The kinematic signature of a central dark mass concentration, however, is very difficult to detect since it requires spectroscopic data with a resolution at the subarcsecond level. NGC 1399 is such a case where the combination of radio, photometric and (stellar) kinematic signatures (each of them alone would not have been conclusive) has led to the confirmation of a central black hole of about 6×10^9 $M_\odot$ (Stiavelli, Møller & Zeilinger 1993).

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Light Curves of Miras Towards the Galactic Centre

C. ALARD[1], A. TERZAN[2], J. GUIBERT[1]

[1]Centre d'Analyse des Images, Observatoire de Paris, France; [2]Observatoire de Lyon, France

Introduction

Long Period Variables represent a late stage in the evolution of stars of intermediate masses. Mass loss, which leads them to planetary nebulae in a few 10^5 years, is a complex process and the object of many investigations. For instance, Vassiliadis and Woods (1993) suggest that mass loss could occur in brief superwind phases separated by long quiescent periods.

A First Step in the Inventory

Here we present the first results of a systematic study of variable objects in a field of about 10 × 10 degrees towards the Galactic Centre. The first step of our

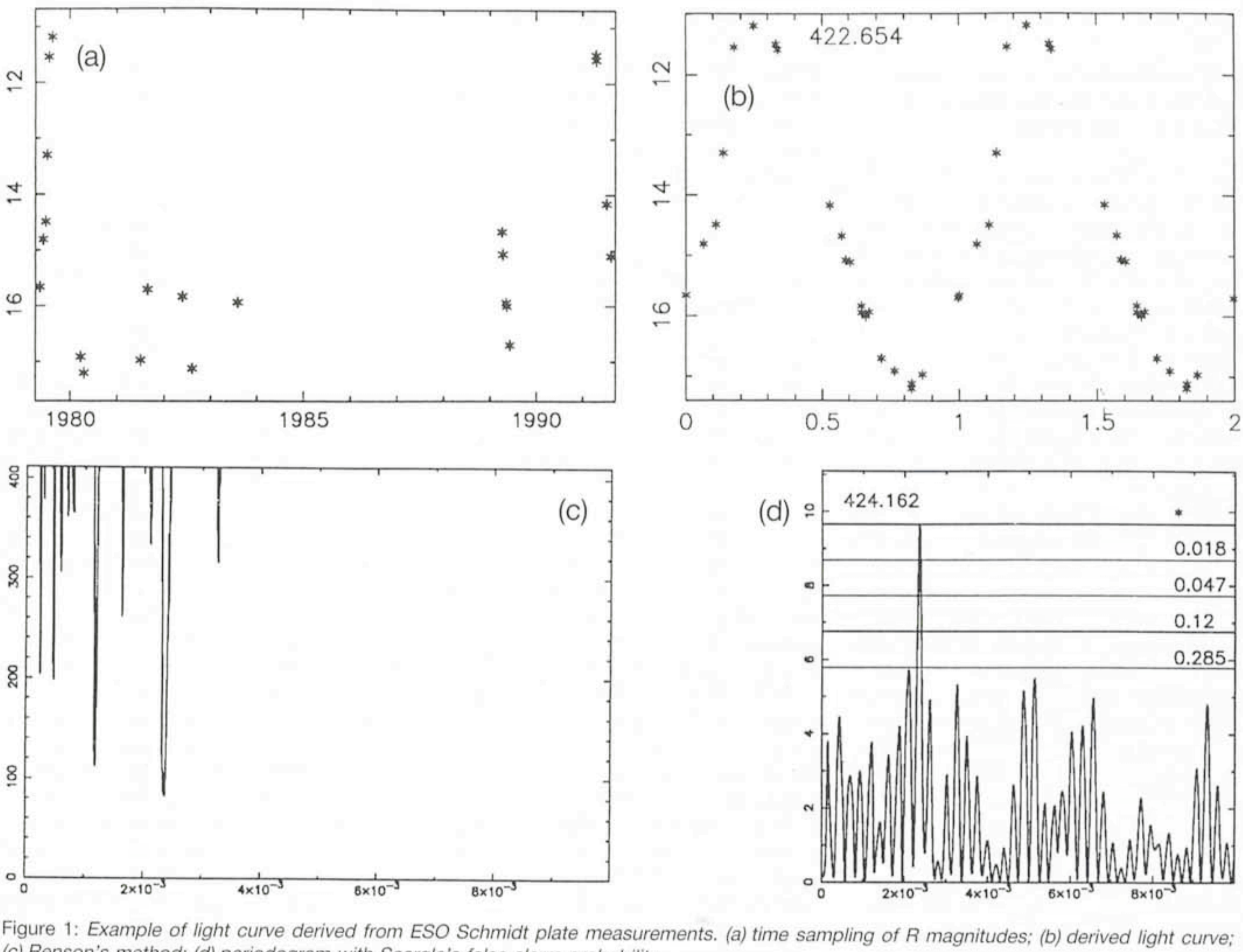

Figure 1: *Example of light curve derived from ESO Schmidt plate measurements. (a) time sampling of R magnitudes; (b) derived light curve; (c) Renson's method; (d) periodogram with Scargle's false alarm probability.*