Strong Gravitational Lensing with SKA

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The advent of new observational facilities in the last two decades has allowed the rapid discovery and high-resolution optical imaging of many strong lens systems from galaxy to cluster scales, as well as their spectroscopic follow-up. Radio telescopes have played the dominant role in the systematic detection of dozens of new arcsec-scale lens systems. For the future, we expect nothing less! The next major ground- and space-based facilities, especially the *Square Kilometer Array* can discover tens of thousands of new lens systems in large sky surveys. For optical imaging and spectroscopic follow-up a strong synergy with planned optical facilities is needed. Here, we discuss the field where strong gravitational lensing is expected to play the dominant role and where SKA can have a major impact: The study of the internal mass structure and evolution of galaxies and clusters to $z \sim 1$. In addition, studies of more exotic phenomena are contemplated. For example, milli- and microlensing can provide a way to measure the mass-functions of stars and CDM substructure at cosmological distances. All-sky radio monitoring will also rapidly develop the field of time-domain lensing.

1. Introduction

Gravitational lensing [5] is the study of the deflection of light-rays from their straight Euclidean path due to the curvature of space-time caused by the presence of matter or energy. Whereas only a curiosity several decades ago, gravitational lensing has rapidly developed into a tool widely used in astrophysics and cosmology. It has already become the preferred method to study dark matter in the Universe, it can be used to study mass scales from planets ($\sim 10^{-4}$ M$_\odot$) to large-scale structure ($\gg 10^{14}$ M$_\odot$) and the conclusions do not depend on the nature of the gravitating mass and its dynamical state. In addition, the large redshift range over which lensing is seen allows one to measure the evolution of properties of the dark and luminous mass distribution, something that is difficult to do in any other way. Here, we discuss the impact that SKA[1] can have on *strong gravitational lensing* – where multiple images of a single background source are formed – and in particular how these lens systems can be used to study the structure and evolution of galaxies and clusters. Some of this will be based on current understanding, but some will necessarily be more speculative. We first set the scene by estimating how many strong-lens systems SKA can discover, based on a large sky survey. We limit the discussion of the more technical details – which have been discussed elsewhere [3] – and focus on the science with an ensemble of lensed systems three orders of magnitude beyond what we have to date.

2. The Radio All-SKA Lens Survey

Based on the current specifications of SKA (October 23, 2003), a Radio All-SKA Lens (RASKAL) Survey of half of the sky (2×10^4 sq. degrees) at 1.4 GHz can be accomplished in about five months (10 min per 1 sq. degree pointing, assuming a single beam.) to a depth of several tenths of μJy per beam with a resolution of 0.01″–0.02″. This survey will undoubtedly be done for many reasons other than lensing. If we limit sources to brighter than 3 μJy[1], this sur-

[1]A signal-to-noise ≥10 per beam will be sufficient for a clear identification of most sources when being lensed. However, since most sources are close to the survey flux limit and every pointing encompasses many lensed systems, deeper follow-up of *all* faint lensed systems will be equivalent to an all-sky survey deeper than 10 min per pointing. For a >1 sq. degree FOV or multiple beams, the effective integration per pointing could be >10 min,

vey yields $\sim 10^5$ sources per square degree or 10^9 sources per hemisphere. Based on the lensing optical depth found from the CLASS radio lens survey [4,2], $\tau = (1.4 \pm 0.4) \cdot 10^{-3}$, one might expect the number of lensed sources to be $N_{\rm lens} \sim 10^6$ if the redshift distributions of the CLASS and SKA sources are similar. Most of these sources are expected to be extended star-burst galaxies, but ∼10% might still be compact flat-spectrum AGNs. The latter, as was the case for CLASS, are easy to identify and yield a number of lensed systems $\sim 10^5$, assuming these AGN are mostly at $z > 1$. The extended sources will appear as arcs and rings, with curvature radii ranging between a few tenths and several arcsec for galaxies and potentially tens of arcsec for clusters. The dominant uncertainty is the typical redshift of starbursters. For sources $> 10\mu$Jy, the median redshift is expected to be $z > 1$ and $\tau \sim 10^{-3}$ for $\sim 10^8$ available sources [3].

In the following we therefore assume $\sim 10^5$ lensed systems with compact flat-spectrum AGN sources and at least $> 10^5$ with extended starburst sources. We should note that the actual *parent population* of the lensed sources can be ∼10 times fainter, and thus more numerous, which increases the above lens-rates. However, the SDSS has taught us that estimating the number of expected lensed systems is easier than identifying them in the actual data. In the following section, we discuss why is SKA is expected to do better in identifying new lens systems.

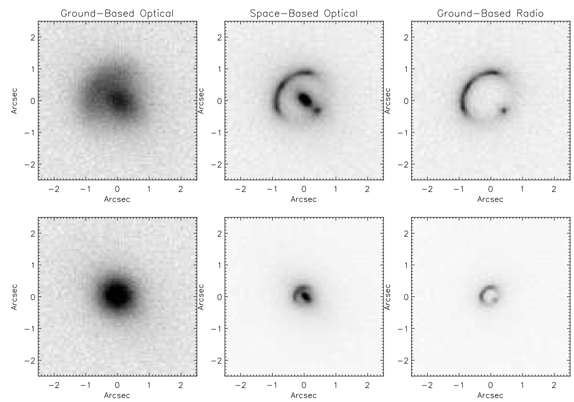

Figure 1. A lens system with a source lensed into a four-image arc/ring. The upper (lower) panels show an early-type lens with an Einstein radius of $R_{\rm E} = 1.2(0.4)''$. From left, middle to right, the FWHM resolution decreases from $0.7''$, $0.1''$ to $0.02''$ (e.g. expected for LSST, SNAP, SKA, respectively). The two right panels show the radio system, as observed with SKA, without the lens galaxies. Note that in the optical the lens-galaxy significantly contaminates the emission from the lensed source, making it harder to identify these systems as lenses, whereas in the radio even small-separation systems are relatively easier to identify. [The lens and source have $R^{1/4}$ brightness profiles with effective radii of $1.5''$. The lens is 5 times brighter than the un-lensed source. The S/N=1 per pixel ($0.05''$) at the effective radius of the lens for each panel (the brightness range is set differently to bring out the structure).]

3. Identification and Expectation of New Lensed Systems

To identify $\sim 10^5$ lensed systems, special search strategies have to be developed. Whereas for $\sim 10^4$ sources with two dozen lensed systems (e.g. CLASS), a search-by-eye is feasible, it clearly is not for $\sim 10^9$ sources. There are several advantages of searching for new lensed systems in the radio, that make this task easier than e.g. in optical surveys: (i) To clearly identify a lens system, at least several resolution elements across the system are needed. The typical image splitting is $\sim 1.2''$ for L_* galaxy lenses with $\sigma \approx 225\,{\rm km\,s^{-1}}$, hindering ground-based optical surveys with comparable seeing (e.g. SDSS). On the other hand, SKA has an anticipated resolution of $0.01''-0.02''$ at 1.4 GHz, more than sufficient to identify even small dwarf-galaxy lenses with $\sigma \approx 50\,{\rm km\,s^{-1}}$ (e.g. Figure 1.) (ii) At 1.4 GHz the emission of a non-starburst early-type lens galaxy (i.e. the dominant lens) is often small compared to the source emission[2]. This improves chances of iden-

increasing the number of lensed systems.

[2]Note that some lens galaxies have radio-bright AGN. The latter, however, are typically compact and seen in the galaxy cores, where emission of the lensed source is

tifying a source as being lensed, in particular if the source is poorly resolved. (iii) The bandwidth of $\Delta\nu/\nu \approx 0.25$ allows disentanglement of complex multiple images (e.g. rings and arcs) based on their spatial spectral-index distribution. (iv) Unlike optical surveys, in the radio lensed images are not affected by dust-extinction, although the most compact μJy sources might scintillate. The latter, however, remains limited at 1.4 GHz due to the small (10 min) integration times and its effect can be assessed from its frequency-dependent behavior within the wide bandwidth.

In the case of compact flat-spectrum AGNs, one can pre-select candidates using only the longest baselines, such that extended emission is resolved out. Multiple compact images within several arcsecond (i.e. galaxy scale) are a good indication of a lensed system, in particular if their low-frequency radio spectra are similar (at $\nu \sim 1$ GHz, these sources are not expected to vary strongly). The case of extended sources is more complex and requires more sophisticated analyzes of the data, for example through neural networks. The high resolution, relatively minor contamination by emission from the lens galaxy and large frequency coverage all contribute to making this task easier, although it remains difficult to assess the completeness of such a strategy. We can neither expect to find *all* lensed systems, nor expect an ensemble to contain only *genuine* lensed systems. Any algorithm that is more restrictive reduces the number of non-lenses in the ensemble, but also also rejects genuine lensed systems[3]. However, *"completeness regions"* might be identified for statistical purposes (e.g. studying galaxy evolution and cosmography).

Assuming that we find $> 10^5$ lensed systems, what type of strong-lens systems can we expect? Simply speaking, all objects with a density greater than $\Sigma_{\rm crit} = 3.5\hat{D}^{-1}$ kg m^{-2} with $\hat{D} = D_{\rm d}D_{\rm ds}/D_{\rm s}$ (distances are in Gpc) can in principle multiply image a source. This includes nearly all collapsed objects in the Universe: *asteroids, comets, planets, brown dwarfs, stars, stellar remnants, primordial black holes, globular clusters, galaxies, some compact groups, and clusters*. Whereas at distances of several kpc only the most dense objects can multiply image (e.g. asteroids, ..., primordial black holes) at cosmological distances of Gpc, the less dense objects (e.g. galaxies, ..., clusters) become the dominant observable lenses. This is because the typical image separation is $\theta_{\rm Einst} = 3(M/M_\odot)\tilde{D}^{-1/2}$ μas, with $\tilde{D} = D_{\rm d}D_{\rm s}/D_{\rm ds}$, which for stars is of order microarcsec and for galaxies and clusters arcsec to arcmin. Whereas current telescopes are limited by their resolution in their ability to find lenses much smaller than galaxies at cosmological distances, SKA with $0.02''$ resolution can discover lensing by objects as small as dwarf galaxies ($> 10^7$ M$_\odot$) or even smaller if SKA is combined with other telescopes in VLBI mode. Even so, the dominant type of lens is determined by the total mass fraction in those objects. Since the total number of lenses is $N_l \propto \Omega_l/M_l$ and the lens cross-section $\sigma_l \propto \theta^2_{\rm Einst}$, the total integrated cross-section of the lens population is $\sigma_{l,tot} \propto \Omega_l$. Hence, structures like galaxies and clusters that dominate $\Omega_{\rm m}$, will also dominate the population of lens systems. We therefore think that their study will be one of the largest beneficiaries of an all-sky strong lens survey.

4. The Internal Structure & Evolution of Galaxies and Clusters

Galaxies and clusters are the most massive collapsed, possibly relaxed, structures in the Universe. Their internal structure and evolution provide clues to how the matter distribution evolves from the linear to highly non-linear regime. Until recently, the mass distribution and evolution of galaxies and clusters have only be studied through their luminous mass, e.g. HI rotation curves, polar rings, X-ray observations and stellar dynamics. Degeneracies in these techniques and the required high–S/N data have limited such studies to the local Universe (i.e. $z < 0.1$).

In the more distant Universe, gravitational lensing provides a practical tool to study their inner mass structure in more detail. Many of the lens systems – to be discovered by SKA –

strongly demagnified.

[3]Note that a by-eye check of 10^5 lensed systems would take ∼4 eight-hour work days, spending only 1 second per lens!

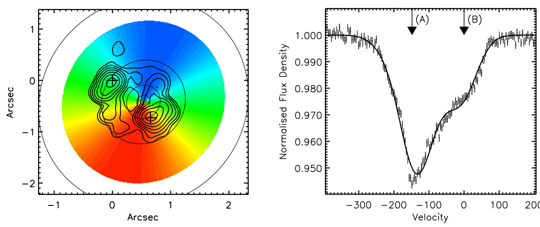

Figure 2. **Left:** A MERLIN 1.4–GHz radio image (contours) of PKS1830–211 overlaid on a model of the HI velocity field in the spiral lens galaxy at z=0.89. **Right:** An integrated WSRT HI absorption line, overlaid with the best-fit model of the line, given the HI velocity field shown in the left panel.

show extended arcs and rings (Figure 2), providing more powerful constraints on the lens potential. Combined constraints with other techniques (e.g. stellar dynamics and high-resolution optical imaging) can help to further disentangle the distributions of luminous stellar mass from the dark-matter halo in early-type galaxies out and beyond $z = 1$. Similar techniques can be used for spiral galaxies and clusters. We now discuss these separately in somewhat more detail.

4.1. Disk-dominated Galaxies

The determination of the mass distribution of disk galaxies has historically been dominated by the study of their rotation curves, sometimes supported by stellar-kinematic data. Even though rotation curves are easy to translate into enclosed mass, it remains nearly impossible to determine their stellar M/L ratios with confidence. In particular at high redshifts, little or no data is available. SKA will offer several opportunities to measure mass profile of disk-dominated galaxies. First, through rotation curves of the more HI-rich disk galaxies to $z \sim 1$. However, several equally exciting opportunities are offered by gravitational lensing[4]: (i) Direct measurement of the total mass profile through lensing-constraints from extended arcs and complete Einstein rings (e.g. B0218+357). (ii) HI-absorption measurements against a lensed radio source, combined with the lensing constraints from the rings/arcs themselves (e.g. PKS1830-211; Figure 2). This provides complementary lensing and kinematic information. Since the brightness of the source does not correlate with the HI content of the lens galaxy, this technique can be used even for dwarf galaxies that are too faint in HI emission. For hundreds of disk galaxies with HI gas and relatively bright background sources, deeper follow-up can be done, to map their kinematic field over the extent of the lensed arcs/rings. A study of disk galaxies to $z > 1$ and possibly as faint as $0.01\,L_*$ (i.e. dispersions $\sigma = v/\sqrt{2} > 50\,\mathrm{km/s}$) can thus be imagined.

4.2. Early-type Galaxies

For early-type lens galaxies very similar studies can be done. However, the complementary kinematic data is obtained from optical spectra obtained with large-aperture telescopes, not from HI gas. Recent studies of early-type galaxies at $z = 0.5 - 1.0$ have shown that gravitational lensing – especially the enclosed mass of the galaxy – allows the mass-anisotropy degeneracy in stellar dynamics to be broken. Constraints can then be set on the mass fraction and inner slope of their dark-matter halos, providing direct evidence for dark matter around these galaxies beyond the local Universe.

The gain is obvious with $\sim 10^5$ new radio-selected lens systems to choose from, instead of the current ∼100 systems of which only a fraction is useful for detailed optical and kinematic follow-up[5]. Properties of the luminous and dark-matter distributions can be studied over a much wider range of parameter space and also in time (i.e. redshift), allowing evolution of the mass distribution of galaxies to be studied directly. Whereas most cosmological studies thus far focus on the evolution of galaxies in terms of their baryonic

[4] Although lens-galaxies are dominated by early-type galaxies, we expect to find at least $\sim 10^4$ disk-galaxy lenses with $L > 0.01\,L_*$ (assuming an image separation $\Delta\theta = 0.04''$ is sufficient to recognize a lens and $\Delta\theta_* = 0.4''$, with $L \propto \sigma^4 \propto \Delta\theta^2$).

[5] Lens surveys that target bright optical sources (e.g. quasars) often limit detailed studies of the fainter lens galaxies.

content (e.g. gas and stars), little to nothing is known about their mass and structural evolution. Strong gravitational lensing with the large samples that SKA can discover will change this situation.

4.3. Clusters of Galaxies

Strong lensing by clusters, although more massive, will be less common. However, with a lensing rate of ∼1:50,000 we still expect thousands of strong lens cases by clusters to be discovered in a RASKAL Survey. Since this is a "blind" survey (i.e. one targets the sources, not the lenses), a sample of cluster lenses can be used to accurately quantify their mass-function with redshift. Such a sample would also be an indicator of the evolution of structure from the linear to non-linear scales, a strong function of the cosmological model. Deep integrations on individual clusters (e.g. identified from deep optical surveys) can unveil a wealth of radio-arcs from the population of extended star-burst galaxies at the μJy level, used to map the inner mass distribution of these clusters in detail. Also weak-lensing studies, beyond the scope of this paper, can be done at par with optical studies (see contribution by Blake et al. in this volume). The great advantage of deep cluster surveys with SKA is that foreground (including cluster) galaxies do not severely "hinder" a study of the lensed background, since they are often relative faint in the radio (i.e. mostly early-type galaxies).

5. Other Lensing Studies with SKA

Besides an extensive quantitative study of the internal structure and evolution of galaxies and clusters to $z \sim 1$, a large sample of new radio-bright lens systems allows more "exotic" studies:

- **Time–Delays:** Intrinsic brightness and structural changes in the lens source will induce correlated variability in the observed lensed images. The different traverse times of photons for these images introduce time-delays that can be measured and used to determine the Hubble constant if the lens mass model is known. However, once SKA comes on line, this and the other cosmological parameters will have been determined with great accuracy already. Time-delays can then be used – given a fixed cosmological model – as a powerful direct measure of the density profile of individual galaxies. A combination of potentially hundreds or thousands of time-delays allow a precise (few percent) determination of the average radial density profile in their inner ∼15 kpc. To select lensed sources that are also variable, the RASKAL Survey has to be designed to make *multiple* passes over the same area. After an initial selection of the brightest and most variable lensed sources, several tens of sources can simultaneously be monitored using SKA's multi-beam capability (if this design is implemented)[6].

- **Micro & Milli–lensing:** Small scale structure in the lens potential – e.g. due to luminous mass (stars, globular clusters, etc.) and, possibly, CDM substructure – can cause differential magnification of the source, on milli- to micro-arcsec scales, and deviations of the lensed image properties (e.g. positions and flux-ratios) from those naively expected from a smooth lens potential. If the structure of the source or the potential change, or their relative alignment on the sky (due to deviations of the lens and/or source velocities wrt the Hubble flow), apparent structural source variability that is uncorrelated between images, can occur. Through this, one can study both the small-scale properties of the lens potential (e.g. their stellar or CDM substructure content) and the radio-source structure on scales unattainable through other methods. With a statistical study of the *structure functions* of thousands of the bright and compact lensed AGNs, one might e.g. be able to disentangle the power-spectra of the source structure from that of the lens potential. If the latter is dominated by stars,

[6] In 1 sec, a S/N∼100 is reached on a 1 mJy source. With one beam, one could monitor *all* 1-mJy sources in the sky in 6 hrs (i.e. 600 times less than RASKAL itself), or in 30 min with ten 1-sq. degree beams.

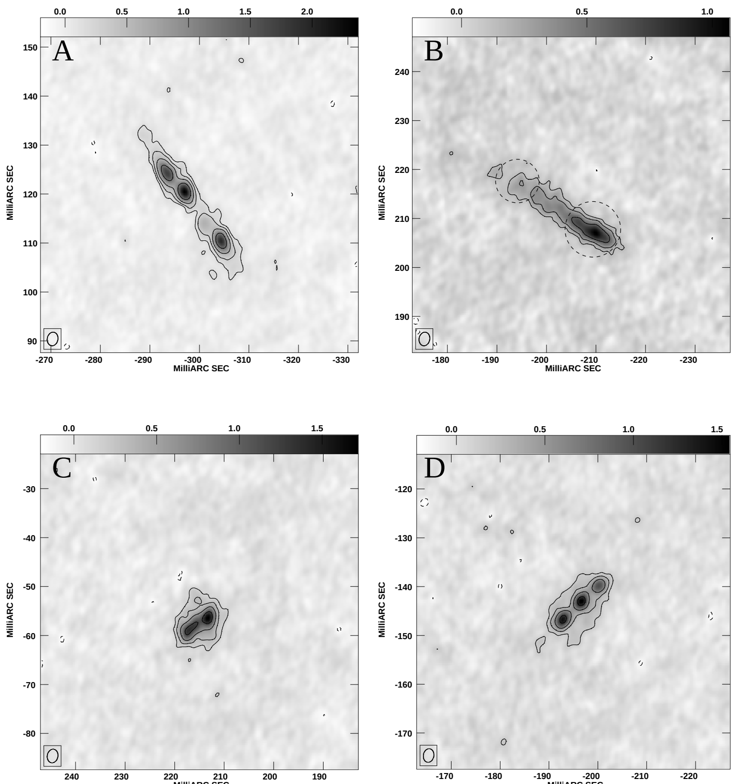

Figure 3. Very-Large Baseline Array (VLBA) radio images of B0128+437 at 5 GHz. Whereas images A, C and D clearly show similar images structure, consisting of three distinctive knots, in image B these knots are nearly gone. Since lensing conserves surface brightness, such dramatic changes are most easily explained by strong scattering due to the ionized lens ISM. With SKA one could similarly probe the ionized ISM of high-z galaxies.

such power-spectra can be used to constrain the stellar mass function in cosmologically-distant galaxies.

- **The Lens–Galaxy ISM:** Radio-wave scattering due to the ionized ISM in the lens galaxy can affect the lensed images (e.g. scatter-broadening and scintillation; Figure 3). The time-scales and frequency dependence of the source variability (both in structure and flux) will be different for milli/microlensing (lensing is achromatic)[7]. By studying the frequency dependent behavior of the lensed images – in particular if the source is scatter-broadened on scales of ∼1 mas – one might be able to constrain the shape and normalization of the power-spectrum of the ionized ISM in the lens galaxies. Hence, scattering and milli- and microlensing are very similar, with the main difference being that in the former case the "scattering screen" is frequency dependent. The mathematical toolbox developed to study scintillation/scattering can thus be applied to milli- and microlensing as well. Since the ionized ISM is related to star formation, such studies can provide a gauge of the amount of star formation in highly-obscured star-burst galaxies. In addition, polarized background sources that are lensed into extended arcs or even rings can be used, through Faraday rotation, to map $\int n_{\rm e} B_{\|} {\rm d}r$ in the lens itself. In the case of clusters, both X-ray and S-Z observations can constrain the electron density $n_{\rm e}$. Hence their large-scale coherent magnetic field, $B_{\|}$, can be quantified and mapped.

[7] Whereas intrinsic variability can be removed because it is correlated between the lensed images, scattering and milli- and microlensing are uncorrelated.

- **High–Redshift Sources:** The use of strong lensing as a "natural telescope", magnifying faint high-redshift source is becoming more important. Source magnifications of $\mu \sim 10$ for example "upgrade" 8–10m class telescopes to a 30m telescope! The magnification of strongly-lensed images that merge near a critical curve is $\mu \sim \theta_{\rm Einst}/\Delta\theta_{12}$, where $\Delta\theta_{12}$ is the angular distance between the two merging images and $\theta_{\rm Einst}$ the Einstein radius of the lens. Whereas ground-based optical images limit $\Delta\theta_{12}$ to $\sim 1''$ and $\mu \sim 30$ for typical clusters with $\theta_{\rm Einst} \sim 30''$, the high resolution of SKA with a limit of $\Delta\theta_{12} \sim 0.05''$ allows radio sources with $\mu \sim 600$ to be found and studied, upgrading SKA to an effective Thousand Square Kilometer Array! Not only does this allow extremely faint sources at high redshift to be found, through the high magnification (mostly linear) details in the source can be studied that otherwise can only be resolved with 10^6 km baselines. We expect this technique to provide the most detailed studies of faint high-z radio sources, possibly the progenitors of AGNs and other faint radio sources at or beyond the epoch of reionization. Per cluster the lensing cross-section, however, is $\sigma(>\mu) \sim \pi\theta^2_{\rm Einst}/\mu^2$. If the source count increases as $N(>S_{\rm obs},\mu) \sim 3 \times 10^5 (S_{\mu{\rm Jy}}/\mu)^{-1}$ per square degree, the number of highly-magnified lensed sources per cluster is $N_l \sim 0.1(\theta_{\rm Einst}/1'')^2(\mu S_{\mu{\rm Jy}})^{-1}$. We might expect hundreds of highly magnified source (with μ>100) from the thousands of clusters observed in a RASKAL Survey.

- **Rare Lensing Events:** Besides these exciting possibilities, the large number of lens systems will naturally produce rare and odd cases of lensing: (1) Lensing by higher-order catastrophes (e.g. hyperbolic umbilics, swallow-tails, etc.), for example, provide large source magnifications and interesting constraints on the lens potential. (2) The radio-afterglows of GRBs can be multiply imaged by foreground galaxies. This not only provides accurate image time delays, but also an opportunity to re-direct *optical, X–ray and other* telescopes to "the place of action" *before* the burst in the other lensed images occur (because of the time-delays). (3) Microlensing of GRB bursts, while multiply-imaged, will further allow a probe into their μas-scale structure during the initial phases. (4) The large number of systems also allows rare cases of extremely small and extremely large image separations to be found by dwarf galaxies and massive clusters, respectively. (5) Although shown to be rare already, collapsed *dark structures* that have no luminous component, can also be found through strong lensing in an unambiguous way if they really exist in significant numbers.

6. The Synergy with Optical Telescopes

To fully exploit the unique capabilities of SKA to discover and study strong gravitational lenses, it is essential to follow-up a significant fraction of these systems at optical wavelengths. The reasons are many-fold: (i) Identification of the lens type (e.g. early- versus late-type galaxies, or other), something that is not always obvious from only the radio observations. (ii) Characterization of the stellar mass distribution, its colors and luminosity. This is particularly important if a serious comparison between luminous and dark-matter properties is planned. (iii) Determination of photo- and/or spectroscopic redshift of the lens and source. (iv) Spectroscopic follow-up to study the kinematics of the lens and its chemical constituents (incl. dust-extinction of the lensed images). (v) Study the highly magnified and high-z source, using the lens as a natural magnifying glass. These are only a few reasons, but it is clear that optical follow-up is needed to fully exploit these lens systems in the context of cosmology, galaxy formation and evolution.

The study of arc-second strong lensed systems has greatly benefited from the high resolution offered by the *Hubble Space Telescope*. With $> 10^5$ lensed systems, however, individual follow-up will not be feasible and deep all or large sky surveys in the optical are the only option. Several instruments are planned that strive toward this, among which are the *Large-aperture Synoptic Survey Telescope* (LSST) and the *Panoramic Survey Telescope & Rapid Response System* (Pan–STARRS). These are ground-based instruments that intend to monitor the entire visible sky, although limited in resolution by atmospheric seeing ($>0.5''$). The space-based *Supernova Acceleration Probe* (SNAP) will image smaller areas of the sky (up to $\sim$300 sq. degrees) with higher resolution ($0.1''$). Powerful deconvolution techniques, however, can be applied to low-resolution, but high S/N, ground-based images to extract the necessary optical information.

With SKA, we expect to find $> 10^{5-6}$ new lensed systems, have $0.5 - 1.0''$ ground-based optical images of most of these and $0.1''$ resolution space-based optical images of $\sim 10^{3-4}$ systems (several percent). Spectroscopic follow-up can probably be done of a similar number of systems with large field-of-view multi-fiber spectrograph's on large-aperture optical telescopes. In particular for kinematic studies this requires at least 8–10m class telescopes, most preferably larger, such as the next-generation of *Extremely Large Telescopes* (ELTs; i.e. > 20 m). Even though essential, the bottleneck of a serious strong-lensing study of the majority of new lens systems that SKA will discover is the optical (or other wavelength) follow-up. This is not only true for lensing studies, but applies to most high–z studies where objects are typically $< 1''$ in size. A serious study is therefore needed how to match optical surveys to the capabilities of SKA, in depth, resolution and sky-coverage, fully exploiting their complementary capabilities.

7. Prospects

The state of lensing is good! And it will drastically improve once SKA comes on line. However, a new telescope is not only built to redo "old stuff" (i.e. old once SKA is build). With a sample of 10^{5-6} strong-lens systems one can explore a much wider range of lens-galaxy or cluster properties (e.g. in mass, luminosity, redshift, etc.). It is hard to break up current samples of a few dozen useful lensed systems in more than a few bins.

The *Square Kilometer Array* will be hard to beat in terms of finding lensed systems, since it has superior resolution over all planned optical telescopes – which also aim to find lensed systems – and the lenses themselves are often faint at radio wavelengths, limiting confusion with the lensed source. However, there is no guarantee that lensed radio sources are also optically bright, which is something that needs to be kept in mind. Even if they are, one can only find out by optical follow-up. This requires a similar all-sky survey in the optical, as planned with LSST and Pan-STARRS. Determining most lens and source redshifts (if not possibly from HI emission), requires spectroscopic follow-up with large field-of-view telescope of at least 8–10m diameter. Because of their more limited sample size, cluster-studies will be less affected by limits on optical follow-up. We expect these issues to be addressed and solved, since they are crucial in many of the studies with SKA.

Once these issues are addressed, SKA can revolutionize the study of the internal structure and evolution of galaxies and clusters through extremely detailed lensing studies in combination with complementary optical (and possibly X-ray) data of large samples. There is currently no obvious "competitive" technique that can do this in an unambiguous way (e.g. HI kinematic studies are limited mostly to gas-rich late-type galaxies). In addition SKA will open up new fields of study at cosmological distances, such as measuring the ionized ISM, the mass function of stars and possibly CDM substructure in high-z galaxies. The resolution and sensitivity of SKA will also allow extremely magnified high-z sources to be found when lensed by clusters (and galaxies alike), providing unique insight into the structure of the faintest and highest redshift population of radio sources that even with SKA are beyond reach when not magnified. Besides the obvious, a large sample will undoubtedly show up more exotic types of lensing (e.g. higher-order catastrophes, lensing of GRBs, etc.) which are just too rare to find with the present limited capabilities and samples.

We conclude to say that through strong gravitational lensing, SKA can have a major impact upon numerous fields in cosmology and astrophysics and undoubtedly open up many new and unexpected avenues of research.

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