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VOLUME 18, 2001



*An international journal of astronomy and astrophysics*

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*Publ. Astron. Soc. Aust.*, 2001, 18, 192–194

# The 2dF Gravitational Lens Survey

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*Received 2001 January 21, accepted 2001 March 7*

**Abstract:** The 2 degree Field (2dF) galaxy redshift survey will involve obtaining spectra of approximately $2.5 \times 10^5$ objects which have previously been identified as galaxy candidates on morphological grounds. Included in these spectra should be about ten gravitationally-lensed quasars, all with low-redshift galaxies as deflectors (as the more common lenses with high-redshift deflectors will be rejected from the survey as multiple point-sources). The lenses will appear as superpositions of galaxy and quasar spectra, and either cross-correlation techniques or principal components analysis should be able to identify candidates systematically. With the 2dF survey approximately half-completed it is now viable to begin a methodical search for these spectroscopic lenses, and the first steps of this project are described here.

**Keywords:** surveys — gravitational lensing — methods: data analysis

## 1 Introduction

It is possible to discover gravitational lenses spectroscopically by searching for quasar emission lines in the spectra of local galaxies. This is the only way to find lenses with low-redshift deflectors; these are particularly valuable as the lens galaxies can be studied in great detail and the timescales for microlensing are short enough to permit a range of interesting measurements (Mortlock & Webster 2000 and references therein). Kochanek (1992) and Mortlock & Webster (2000) calculated the expected event rate, and several tens of spectroscopic lenses should be forthcoming from the current generation of galaxy redshift surveys (GRSs).[1]

The first large GRS, the Center for Astrophysics (CfA) survey (Geller & Huchra 1989), resulted in the discovery of the lens Q 2237+0305 (Huchra et al. 1985), although it was an essentially serendipitous event. There have been no other quasar lenses discovered in this manner, but several searches for lensed emission line galaxies have been undertaken. The only confirmed spectroscopic discoveries were the two Einstein rings found by Warren et al. (1996) and Hewett et al. (1999) in their sample of large elliptical galaxies. Even though there are only several hundred galaxies in the survey, the regularity of their spectra is such that a very sensitive search for discrepant emission lines is possible (Willis et al. 2001); several more candidates have been identified and are awaiting re-observation. Hall et al. (2000) also announced the identification of several candidate lenses in the Canadian Network for Observational Cosmology (CNOC) GRS (Yee et al. 2000), although these too are yet to be confirmed. The next generation of galaxy survey is exemplified by the Sloan Digital Sky Survey (SDSS; York et al. 2000) which, with $\sim 10^6$ galaxy spectra, should yield at least 50 spectroscopic lenses (not to mention the several hundred lenses expected to be resolved in the imaging survey). The SDSS has only recently got under way, but, at the time of writing, over $5 \times 10^4$ spectra have been obtained, and the pipeline reduction software should be able to select lens candidates with some reliability, although none have been announced so far.

This paper details the beginnings of a lens survey based on the spectra taken as part of the largest existing galaxy sample, the 2 degree Field (2dF) GRS (Section 2). After a brief discussion of the lens statistics (Section 3), the possible spectral analysis methods are examined (Section 4). These points are summarised in Section 5.

## 2 The 2dF Galaxy Redshift Survey

The 2dF GRS (e.g. Folkes et al. 1999; Cole et al. 2001) is, formally, a spectroscopic survey of $\sim 2.5 \times 10^5$ extended images, all of which have isophotal magnitudes brighter than $B_J = 19.45$. The data are obtained using the 2dF instrument, an automatically-configurable multi-fibre spectrograph on the Anglo-Australian Telescope (AAT). The $\sim 10^5$ spectra obtained so far have a resolution of about 10 Å, and cover the range from $\sim$3700 Å to $\sim$8100 Å. Whilst the wavelength calibration is excellent, there have been some problems with the flux calibration, and so continuum levels remain quite uncertain. The spectra are typically the result of 45-minute integrations, and so the signal-to-noise ratio in each pixel is between $\sim$10 and $\sim$20 for an object at the survey limit.

It is expected that $\sim$95 per cent of the objects selected for the survey will be local galaxies, with the remainder being mainly misidentified Galactic stars. However a few of the survey galaxies will be multiply-imaging background quasars, and, if the quasars are sufficiently bright, should be identifiable as gravitational lenses. Two main questions present themselves at this point: how many lenses might be detectable in these spectra, and what is the best way to find any lenses that might be present?

[1]The use of existing spectra is critical to the efficiency of this method; this is discussed elsewhere in this issue by Mortlock & Drinkwater (2001).


10.1071/AS01021 1323-3580/01/020192$05.00

The answers are related, in so far as any given search method is linked to the effective 'depth' of the lens survey, but it is possible to obtain an estimate of the number of lenses without fully understanding how to find them.

## 3 Lens Statistics

Kochanek (1992) and Mortlock & Webster (2000) applied standard techniques to determine the rate of lensed quasars expected in a generic GRS, and a more detailed calculation verified these results for the 2dF survey (Mortlock & Webster 2001). The number of lenses depends principally on two factors: the depth of the survey and the quality of the spectra. The latter, potentially a somewhat ambiguous notion, can be characterised in terms of $\Delta m_{\rm qg}$, which is defined as follows (Kochanek 1992): for a lens in which the galaxy has magnitude $m_{\rm g}$ and the quasar images have total magnitude $m_{\rm q}$, the presence of the quasar emission lines is detectable if $m_{\rm q} \leq m_{\rm g} + \Delta m_{\rm qg}$, but the quasar is undetectable if it is fainter than this. The value of $\Delta m_{\rm qg}$ clearly increases with the integration time of the observations, but is also critically dependent on the properties of galaxy and quasar spectra. Kochanek (1992) estimated $\Delta m_{\rm qg} \simeq 4$ for the SDSS spectra, and Mortlock & Webster (2000) used $\Delta m_{\rm qg} \simeq 2$ for the lower quality 2dF spectra. These figures then led to the estimate that the 2dF GRS should yield about 10 lensed quasars (Mortlock & Webster 2000), although it could be as low as $\sim$5 (if $\Delta m_{\rm qg} \simeq 1$) or as high as $\sim$20 (if $\Delta m_{\rm qg} \simeq 3$). Fortunately the value of $\Delta m_{\rm qg}$ appropriate to a given search technique can be evaluated by analysing simulated composite lens spectra.

## 4 The 2dF Gravitational Lens Survey

The process of finding lensed quasars in the 2dF galaxy spectra can be split into three quite distinct phases. The first of these is the identification of candidate lenses on purely spectroscopic grounds. The vast majority of the spectra should be uninteresting, at least in the present application, but a small fraction should stand out as having either unusual continua, or, more likely, what may be broad emission lines. This set of (probably) several thousand spectra will include white dwarfs, unlensed quasars misclassified as extended sources, and, with luck, several lensed quasars. The second phase of the analysis is to examine each spectrum in detail (possibly by eye) with a view to removing all those objects which are clearly not quasars. This step could also profitably include using any other data which are already available, such as images from the Digitized Sky Survey or the Schmidt plates from which the 2dF objects were selected. Finally, the (hopefully) small set of strong lens candidates would have to be imaged at high resolution ($<$1 arcsec) with a view to determining their nature morphologically. In terms of quantifiable resources this last step is by far the most expensive, as the automatic spectral analysis should take less than a second per object. However the opposite is true when intellectual effort is considered, as the manual inspection of the initial candidate list and (especially) the imaging observations are conceptually straight-forward. The complex task is in determining how best to find a subset of the survey spectra that contains all the lenses and not too much else.

One approach to this problem would be to work backwards — if it is assumed that all the detectable lenses will primarily have broad quasar emission lines then the task reduces to that of identifying the spectra that have emission line–like features. Cross-correlation techniques, combined with continuum removal, could certainly detect some such objects. Unfortunately many galaxy spectra also have features that could be confused with the broad lines of a fainter, superimposed spectrum. Further, this is clearly an inefficient procedure, as much of the available information remains unused. Finally, such a method becomes increasingly difficult once any attempt is made to include non-Gaussian effects such as variation in the continuum levels and the presence of sky lines.

The method that has been adopted is based on Monte Carlo simulations of a large number of lenses. Using the formalism described in Mortlock & Webster (2000) it is possible to generate deflector–source pairs that reflect the variation in lensing likelihood with source redshift and deflector properties. A galaxy–quasar pair generated in this way is a composite object with only one degree of freedom: the relative contribution of the two components to the resultant spectrum. This is very sensitive to the properties of the lens, but such details need not be treated explicitly as the range of possible weightings can be analysed without knowing the actual image configurations. The most important aspect of this method is that, for a given galaxy–quasar pair, a very realistic composite spectrum can be generated by simply combining real 2dF galaxy and quasar spectra. The noise properties of the spectra are certainly correct provided both spectra are kept in their observed frame; the one possible important omission is reddening of the background quasar by dust in the lens. This too can be included in the simulations, but it would incur the penalty of parameterisation; this process is otherwise model–independent. A promising candidate for the analysis method is principal components analysis (PCA; Murtagh & Hecht 1987), which is already being used extensively within the 2dF collaboration, and is well suited to the task at hand. The survey galaxies cover a definite region in the multi-dimensional space of component coefficients (e.g. Folkes et al. 1999) and the lenses should inhabit a contiguous region, with the distance from the galactic locus increasing with the brightness of the quasar component. Unfortunately this process has not yet been implemented; the central ideas are quite clear, but quantitative estimates of the completeness and efficiency of the lens survey cannot yet be made.

## 5 Conclusions

It should be possible to find $\sim$10 gravitationally–lensed quasars in the 2dF GRS spectra. Cross-correlation techniques can be used to search for quasars' emission lines, but a more powerful (and more simply implemented)

https://doi.org/10.1071/AS01021 Published online by Cambridge University Press

scheme is to generate large numbers of simulated lens spectra and to then analyse them using existing software. If the quasar and galaxy spectra used are taken from the 2dF samples this method has the enormous advantage of automatically including various subtleties of the survey data, without the need for detailed modelling. By identifying the regions of parameter space inhabited by these spectra, it is possible to characterise the sensitivity of the lens search (effectively measuring the $\Delta m_{qg}$ parameter discussed in Section 3). More importantly, the real spectra that fall into the same regions of parameter space are immediately identifiable as candidate lenses. Implementation of these techniques should bring the first positive results within the next year.

## Acknowledgements

Thanks to Rachel Webster for first suggesting this avenue of investigation, and also to the entire 2dF survey team; their support will be critical to the success of this project. DJM is funded by PPARC.

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https://doi.org/10.1071/AS01021 Published online by Cambridge University Press