EUROPEAN SOUTHERN OBSERVATORY

Organisation Européenne pour des Recherches Astronomiques dans l'Hémisphère Austral
Europäische Organisation für astronomische Forschung in der südlichen Hemisphäre

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APPLICATION FOR OBSERVING TIME PERIOD: **63**

To be submitted only to: proposal@eso.org
Important Notice:

By submitting this proposal, the PI takes full responsibility for the content of the proposal, in particular with regard to the names of COIs and the agreement to act according to the ESO policy and regulations, should observing time be granted

1. Title Panel: **O–6**
PROBING COSMOLOGICAL SCENARIOS FROM COSMIC SHEAR MEASUREMENTS

2. Abstract
We propose to continue with FORS, as a normal programme, the observations we started with SUSI, as a Key programme. Due to the delays imposed by ESO to our project it is scientifically more competitive and observationally more suitable to benefit of the image quality of FORS, the seeing of of Paranal and the availability of service observing on the VLT than to continue on the NTT.
We propose to measure the polarization of faint galaxies lensed by large-scale matter distribution in the Universe. Observations of 27 FORS fields will provide a unique opportunity: to measure the cosmic shear along several unbiased directions, to distinguish between cosmological models *without* referring to assumptions about biasing and to measure the power spectrum of the (dark) matter distribution in the Universe.

3.

Run	Telescope	Instrument	Time	Month	Moon	Seeing	Obs. Mode
A	UT1	FORS1	32h	sep	d	$\leq 0.8''$	s

4.

Number of nights/hours	Telescope(s)	Amount of time
a) initially requested for this project:	NTT	20n
b) already awarded to this project:	NTT	6n
c) required to complete this project:	UT1	4n

5. Special remarks
This proposal is an alternative to the NTT key programme, which was granted of 20 nights but received only 6. If it is accepted, then we cancel our NTT Key program. If it is rejected then we will continue on the NTT.

6. Principal Investigator: **Y. MELLIER** (Institut d'Astrophysique de Paris, F, mellier@iap.fr)
CoI(s): F. Bernardeau (CEA/SPhT, F), B. Fort (IAP, F), B. Jain (J. Hopkins, USA), R. Maoli (IAP, F), P. Schneider (MPA, D), S. Seitz (MPA, D), L. van Waerbeke (CITA, OTHER)

7. Is this proposal linked to the PhD thesis preparation of one of the applicants?

8. Description of the proposed programme

A) Scientific Rationale: One of the main goals of modern cosmology is to understand the distribution of matter in the Universe. Much progress has been made in the last decade on theoretical, numerical and observational fronts. For example, for a given cosmogony, the statistical properties of the matter distribution can be calculated with high accuracy using very large cosmological N-body simulations. The comparison with observations is, however, hampered by the fact that these simulations predict the distribution of the *dark matter*, whereas redshift and deep imaging surveys of clusters and galaxies probe the distribution of *luminous matter*. The relation between these two distributions is not well understood, and one has either to envoke a biasing factor (Bardeen et al. 1986) for the relative fluctuations of luminous and dark matter, or to model the formation and evolution of galaxies in dark matter halos (e.g., Kauffmann, Guiderdoni & White 1994) – however, this requires assumptions about processes, like star formation, heating, supernova feedback, and galaxy merging, which are not well understood as well.
Gravitational lensing can obtain information about the *total* mass distribution regardless the the state and nature of the matter. In particular, weak lensing studies (for reviews, see Fort & Mellier 1994; Schneider 1996, Mellier 1999), triggered by the paper of Kaiser & Squires (1993), have investigated the mass distribution in about a dozen clusters of galaxies (see Mellier 1999 for a recent review).
Blandford et al (1991), Miralda-Escudé (1991), Kaiser (1992) and Villumsen (1996a) have estimated the shear caused by large-scale structures (LSS) of the matter distribution in the Universe, which leads to correlated ellipticities (or polarization) of the images of faint high-redshift galaxies. Their conclusion has been that the rms polarization on small angular scales is of order of two percent, depending on the cosmological model. This estimate is, however, based on the linear theory of gravitational instability. An heroic attempt to measure this "cosmic shear" has been carried out by Mould et al (1994), using a deep image taken with the Palomar 5m telescope. They obtained an upper limit of the mean image polarization within a circle of radius $\approx 5'$ of 4%. Using a less conservative analysis of the same data, Villumsen (1996b) determined a mean polarization of about 2.5%, with formal 95% confidence errors of $\pm$ 1.2% .
Recently, Jain & Seljak (1997) have included the full non-linear evolution of the density power spectrum. They predict that the polarization on small scales (say, in circles of $1'$) is increased to about 5% rms (see Fig.1). *This result is very encouraging since it means that the cosmic shear is measureable with existing instruments,* provided the image quality is excellent and the seeing is below $\sim$ 0.7arcsec. Indeed, the cosmic shear has most likely been detected: Fort et al. (1996) studied the shear field around several high-redshift QSOs with the NTT and CFHT, and found a significant shear in some of these fields. Their detection has been confirmed by Schneider et al (1998a) and by recent HST observations as well of one of their fields (Bower & Smail 1997). Since these observations were not targeted towards a known mass concentration (like a cluster), this detected shear is due to the LSS – whereas it has been possible to detect galaxy concentrations in some of these fields, which might be responsible for the detected shear if they correspond to mass concentrations, these would be just the non-linear features of the LSS matter distribution. This detection was possible by (1) the good seeing during the observations (below 0.8 arcsec), and (2) due to the superb image quality of the NTT/SUSI instrument.
Two statistical properties of the cosmic shear turn out to be calculable analytically in the fully non-linear regime: the expectation value $p(\theta)$ of the rms value of the polarization in circles of angular radius θ, and the two-point correlation function $C_{pp}(\theta)$ of the polarization. They are not independent, but depending on the geometry of the observing frames, one or the other is easier to measure. Both depend on the assumed cosmological model: on angular scales around $1'$, the rms polarization $p(\theta)$ is predicted to be $\sim$ 5%. For lower Ω the signal is weaker, as shown in Figure 1 where $p(\theta)$ is plotted for 3 different values of Ω for a CDM spectrum with the shape parameter $\Gamma = 0.25$. The spectra are normalized to $\sigma_8 = 1$. For COBE-normalization, $p(\theta)$ would be higher for the $\Omega = 1$ model, and lower for the $\Omega = 0.2$ model – thus the sensitivity to Ω would be even higher. If one wishes to obtain a model-independent estimate of cosmological parameters, then measurements on 2 different angular scales are needed. This is because p is determined by σ_8 and Ω; the dependence on scales of a few arcminutes is $p(\theta) \propto \sigma_8^{1.3}\,\Omega^{0.7}$. Thus for a given physical model normalized to COBE, Ω can be determined, but in general it is the combination of σ_8 and Ω that is measured by $p(\theta)$. The goal can be accomplished using the capabilities of FORS1, from measurements on differents scales: $\approx$ 1' and $>$ 10'.
In addition, Schneider et al (1998b) have proposed the so-called $M_{\rm ap}$-statistics as a measure for cosmic shear. It has the property that its dispersion yields a very well located measurement of the power spectrum of the cosmic density fluctuations at a wavelength given by the scale of the fields used, whereas the other two statistcs are very broad-band measures of the power spectrum.

B) Immediate Objective: We propose an observing program to measure the cosmic shear, or more precisely, $p(\theta)$, $M_{\rm ap}(\theta)$ and $C_{pp}(\theta)$, on angular scales larger than about 1 arcminute. This program involves several steps: (1) From the FORS1 Users Manuel, we plan to use the expected image quality of FORS1 to measure the shear in 40 fields. In a first step (Period 62), we shall observe 12 fields (and adding the 2 already observed with SUSI1). The fields will be selected such that (a) they have a minimum separation of 1 degree (on these scales, the polarization correlation function has dropped to nearly zero - see Fig. 2 - so that shear measurements in the fields are mutually independent) and (b) that they contain a small, but finite, number of (not too bright)

8. Description of the proposed programme (continued)

stars which allow to control the PSF accross the field. This will provide a measurement of $p(\theta)$ and $M_{\rm ap}(\theta)$ on scales of $\sim 2'$ with a $\approx 20\%$ accuracy. As can be seen from Fig. 1, this accuracy is sufficient to distinguish high- and low-density CDM universes with a given variance of the mass fluctuation in a top-hat window of radius $8h^{-1}$ Mpc, σ_8 (for COBE-normalized spectra, the difference is even larger). In addition, $C_{pp}(\theta)$ on small scales ($\theta < 6'$) can be measured and compared to theoretical expectations (see Fig. 2), which yields an additional discriminator between different cosmogonies. These observations will provide the first detection of cosmic shear along several unbiased lines-of-sight (the fields selected by Fort et al. 1996 were chosen to contain a bright radio QSO and to test the magnification bias hypothesis for these objects - thus these fields may be biased towards matter overdensities which are responsible for magnifying the QSO). 2) The measurement of $p(\theta)$ on small angular scale does not uniquely single out one of the currently discussed cosmogonies. To distinguish between them, the polarization must be measured on larger angular scales. We plan to investigate the cosmic shear on larger scales with 26 FORS1 fields (Period 63), measuring $C_{pp}(\theta)$ on scale up to 30'. This will be done by placing the 26 FORS1 fields in a geometric arrangements relative to each other chosen so as to give a minimal variance measurement of $C_{pp}(\theta)$. Statistically combining the total 40 fields, $p(\theta)$ and $M_{\rm ap}(\theta)$ can be measured to 10% accuracy on an arcminute scale. 3) In addition to analytic calculations of $p(\theta)$, $M_{\rm ap}(\theta)$ and $C_{pp}(\theta)$, we are currently performing calculations, using the (already existing) outputs of very large high-resolution N-body simulations, to further investigate statistical measure of the shear which extends beyond two-points statistics and which may provide stronger constraints on the mass fluctuation spectrum due to the non-Gaussianity of the shear field. This latter fact also necessitates the use of numerical simulations to obtain an accurate value for the accuracy of $p(\theta)$, $M_{\rm ap}(\theta)$ and $C_{pp}(\theta)$ as determined from our observations. ogether, these observations will thus:

(a) detect the cosmic shear; measure its rms dispersion on fields of a few arcminutes and the two-point correlation function up to $\approx 30'$;

(b) distinguish between different cosmogonies;

(c) provide a *direct* measurement of the power spectrum of the LSS, independent of assumptions about biasing, etc... on scales which cannot be probed with CMB experiments. The measurements of the shear on small scales will be carried out in two different and completely independent ways. One method is to measure the (complex) ellipticity of galaxies, using both standard software like IRAF, and the methods proposed by Bonnet & Mellier (1995) and Kaiser, Squires & Broadhurst (1995). Averaging these ellipticities yields an unbiased estimate of the mean shear in the field. The uncertainty of this polarization measurement is solely determined by the intrinsic ellipticity of the galaxies and the observable density of galaxies images with sufficient S/N. The second method is the measurement of the distortion of the autocorrelation function (ACF) of the (extragalactic) background light (van Waerbeke et al 1997). he relation between the measured ellipticity and the LSS power spectrum depends on the redshift distribution of the faint galaxies, $p \propto \langle z \rangle^{0.55}$. Whereas little is known about that presently, rapid progress is made by spectroscopic surveys carried out by several groups. Thus, we expect that by the time our data are analyzed, the redshift distribution of the galaxies will be very well constrained. Hence, as a result of the program we will not only obtain the first measurement of the cosmic shear along unbiased lines-of-sight, but the quantitative analysis of our data will yield strong constraints on the cosmological parameters and the shape of the power spectrum of cosmic density fluctuations in the quasi-linear and non-linear regimes.

References: Bardeen, J. et al 1986, ApJ 304, 15. Blandford, R. D. et al 1991, MNRAS 251, 600. Bonnet, H., Mellier, Y. 1995, A&A 303, 331. Bower, R. G., Smail, I. 1997, MNRAS 290, 292. Fahlman, G. et al 1994, ApJ, 437, 56. Fort, B., Mellier, Y. 1994, A&AR 5, 239. Jain, B., Seljak, U. 1997, ApJ 484, 560. Kaiser, N. 1992, ApJ 388, 272. Kaiser, N., Squires, G. 1993, ApJ 404, 441. Kaiser, N. et al 1995, ApJ 449, 460. Kauffmann, G. et al 1994, MNRAS 267, 981. Mellier, Y. 1999, ARAA in press. Miralda-Escudé, J. 1991, ApJ 370, 1. Mould, J. et al 1994, MNRAS 271, 31. Schneider, P. et al A&A in press. Astro-ph/9705122. Schneider, P.et al 1998, MNRAS in press. Schneider, P. 1996, in *The Universe at High-z, Large-Scale Structures and the Cosmic Microwave Background.* Lecture Notes in Physics 470. Springer. Seitz, C. et al 1996, A&A 314, 707. Squires, G. et al 1996, ApJ 461, 572. Van Waerbeke, L. et al 1997, A&A 317, 303.

C) Telescope Justification: The VLT equipped with FORS1 looks an ideal configuration for this program. The survey efficiency is multiplied by a factor of about 4 due to the collecting power of the VLT, FORS1 has excellent image quality, Paranal has a better median seeing than La Silla and service observing permits to observe only during the subarcsecond seeing nights. This is critical for these observations where image quality necessary. So instead of 13 additional nights at NTT, we can complete the survey in 4 VLT nights!

D) Observing Mode Justification (visitor or service): Suit perfectly a service observing schedule.

E) Strategy for Data Reduction and Analysis: The applicants have good experiences with CCD observations on large telescopes and data reduction of ultra-deep subarcsecond imaging for weak shear measurement. They already observed and reduced data from NTT/SUSI and determined weak shear along the lines of sight of bright QSOs below 5% on arcminute scales (Fort et al 1996, Schneider et al 1998). In addition, as TERAPIX project scientist the PI has large experience in data processing and pipeline data reduction.

8. Attachments (Figures)

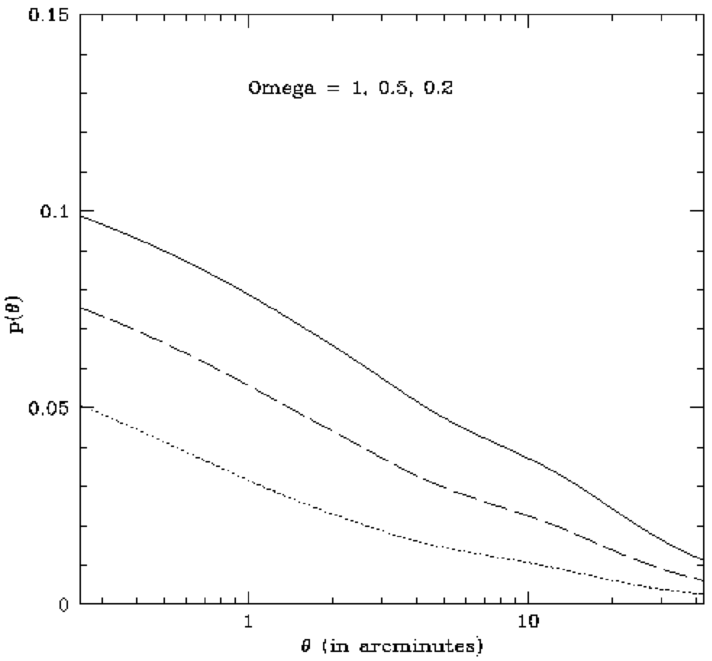

Fig.1

$p(\theta)$ for CDM spectrum ($\Gamma = 0.25$, $\sigma_8 = 1$) and $z_s = 1$. $\Omega = 1$ (solid), $\Omega = 0.5$ (dashed), $\Omega = 0.2$ (dotted).

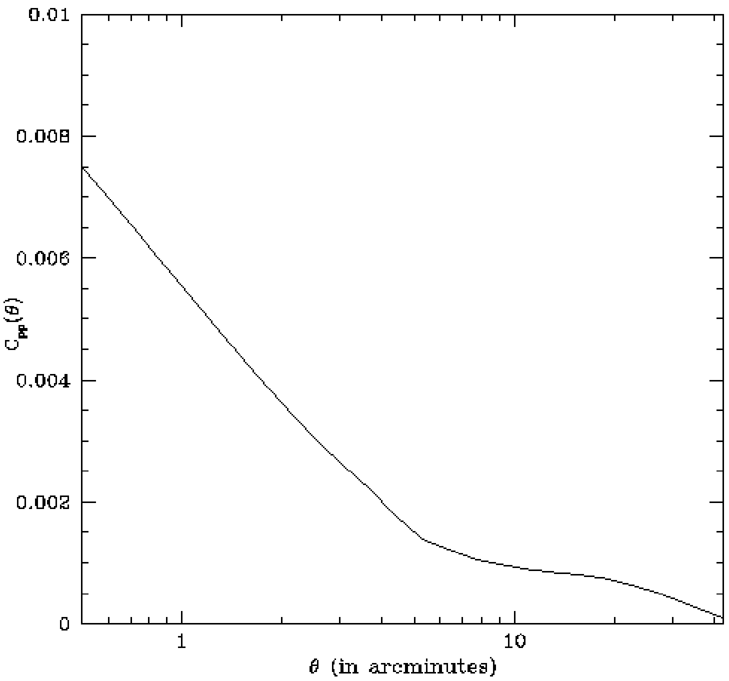

Fig.2

$C_{pp}(\theta)$ on θ for the $\Omega = 1$ CDM spectrum. At 30' the value of C_{pp} is less than 0.1 its value at 1'.

8. Backup Programme

This programme proposed for the VLT has a strategy which makes sense only in case of service observing. So we do not propose any backup programme.

9. Justification of requested observing time and lunar phase

Time Justification: In order to estimate the cosmic shear, we need to control the field-to-field fluctuations due to cosmic variance. A minimum of 40 different fields separated by at least 1^o is needed to obtain one point for the low-density mass fluctuation with a 25% accuracy on $\sim$ 3 arcminute scale. This part of the programme was expected with the SUSI2 data. However, we have been awarded by ESO of only 6 nights over the 10 recommanded. To avoid a decrease of the competitiveness of our programme it seems better to switch to the VLT to complete the observations of the 27 remaining fields. The shear will be measured by using two independent methods: **(a)** the pixel-to-pixel autocorrelation function whose signal-to-noise ratio depends on the total number of galaxies detectable down to the noise level (van Waerbeke et al 1997). The expected rms shear due to non-linear fluctuations is $\approx$ 5% (Jain & Seljak 1997). From Fig. 3 of van Waerbeke et al, this corresponds to an *observed* shear of 1%. Such a low value has already been measured with SUSI in the fields of radiosources, where the rms residual of ellipticities on stars is about 0.3% (Fort et al 1996). This shows that it is technically possible with FORS1 according to the technical descriptions of the instrument. The van Waerbeke et al's figure also shows that an observed shear of 1% is measurable provided the signal-to-noise ratio of the ACF is larger than 100. By using 28 FORS1 fields of $6.5'$, Eq. (44) of van Waerbeke et al shows that a typical galaxy number density of 45 gal/sq-arcmin. will permit to meet the scientific goals. This galaxy number density is obtained for I=25 (The I-band minimizes atmospheric dispersion), that is within 1.2 hours with FORS1, with a signal-to-noise of 3, for an extended object with typical size of 1.5" and with typical seeing of 0.75". Thus, we can observe seven fields per night, so we request 32 hours for the whole program. **(b)** Using software specifically designed for measuring image ellipticities of very faint galaxies, and to correct them for PSF anisotropies plus calibrating the relation between the observed ellipticities and the shear. The result will be compared on a field-by-field basis with method **(a)** and consistency of the results will be required in order to ensure the integrity of the derived shear measurements. The selected field will be close to zenith ($\pm$ 30^o) and have at least 40 stars, for calculation of the instrumental distortion. Each field will be randomly selected in areas of several degrees.

Lunar Phase Justification: Dark.

10. Report on the last use of ESO facilities

62.O-288 / Y. Mellier / Probing Cosmological Scenarios form Cosmic Shear Measurements

Telescope	Instrument	Obs. Dates	Completion (%)	Time lost (%)	Reason
NTT	SUSI1	Dec.97	2.5%	97.5%	technical
NTT	SUSI2	Oct.98	15%	0%	technical
NTT	SUSI2	Nov.98	15%	0%	technical

Current status of obtained data: reduced

Remarks: The data are processed but we need the P62 observations (oct. and nov. 98) prior to analyse them.

11. Applicant's publications related to the subject of this application during the past two years

Bernardeau, F., van Waerbeke, L., Mellier, Y., 1997, A&A 322, 1.

Jain, B., Seljak, U. 1997. *Ap. J.* 484:560-73.

Schneider, P., Van Waerbeke, L., Mellier, Y., Jain, B., Seitz, S., Fort, B. 1998a. *Astron. Astrophys.* 333:767-78.

Schneider, P., Van Waerbeke, L., Jain, B., Kruse, G. 1998b. *MNRAS* 296:873-92.

Van Waerbeke, L. 1998a. *Astron. Astrophys.* 334:1-10.

Van Waerbeke, L. 1998b. Preprint astro-ph/9807041.

12. List of targets proposed in this programme

Run	Target name	α	δ	Equinox	Mag.	Diam.	Additional information
A	KPCS1	+00 17	-20 00	2000	I=25		I.

Target Notes: The targets will be chosen as function of the schedule and the opportunity of service observing. A list of 60 targets has been provided to ESO using the P2PP software. It contains fields for any periods, in order to be flexible. They are all randomly selected areas, far from the galactic plane.

13. Scheduling requirements

14. Instrument configuration

Telescope	Instrument	Parameter	Value or list
UT1	FORS1	Imaging	Direct