iCosmo: an Interactive Cosmology Package

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ABSTRACT

\textbf{Aims.} The interactive software package iCosmo, designed to perform cosmological calculations is described.

\textbf{Methods.} iCosmo is a software package to perform interactive cosmological calculations for the low redshift universe. The computation of distance measures, the matter power spectrum, and the growth factor is supported for any values of the cosmological parameters. It also performs the computation of observables for several cosmological probes such as weak gravitational lensing, baryon acoustic oscillations and supernovae. The associated errors for these observables can be derived for customised surveys, or for pre-set values corresponding to current or planned instruments. The code also allows for the calculation of cosmological forecasts with Fisher matrices which can be manipulated to combine different surveys and cosmological probes. The code is written in the IDL language and thus benefits from the convenient interactive features and scientific library available in this language. iCosmo can also be used as an engine to perform cosmological calculations in batch mode, and forms a convenient evolutive platform for the development of further cosmological modules. With its extensive documentation, it may also serve as a useful resource for teaching and for newcomers in the field of cosmology.

\textbf{Results.} The iCosmo package is described with various examples and command sequences. The code is freely available with documentation at \textit{http://www.icosmo.org} along with an interactive web interface and is part of the Initiative for Cosmology, a common archive for cosmological resources.

\textbf{Key words.} cosmology – observables – numerical methods

1. Introduction

Cosmology is a rapidly advancing field thanks to recent progress in instrumentation, numerical simulations and theoretical methods. The last few decades have provided a previously inaccessible wealth of data with the advent of large surveys of the cosmic microwave background, galaxy clustering, weak gravitational lensing, clusters and supernovae (see Spergel et al.\textsuperscript{2007}, Dunkley et al.\textsuperscript{2008}, for recent results and references therein).

One of the challenges of cosmology is to link the observables which can be derived from these cosmological surveys with the parameters of an underlying cosmological model. Another necessary task is to predict the performance of future surveys and future observational probes in order to maximise the potential of planned experiments. Existing publicly available computational tools (Seljak & Zaldarriaga\textsuperscript{1996}, Lewis et al.\textsuperscript{2000}, Lewis & Bridle\textsuperscript{2002}) are widely used within the cosmological community, yet there does not exist at present a unified tool which considers the low redshift universe and its associated probes.

In this paper, we present iCosmo, a software package to perform interactive cosmological calculations. The code can also be used as an engine to perform predictions for any cosmological model and also forms a convenient platform for the development of further cosmological modules. With its extensive documentation, it may also serve as a useful resource for teaching and for newcomers in the field of cosmology.

The code performs the calculation of distance measures, the linear and non-linear matter power spectrum, the growth factor, volume elements and other quantities for any CDM cosmological model. It also performs the computation of observables for several cosmological probes such as weak gravitational lensing, baryon acoustic oscillations (BAO) and supernovae. The associated errors for these observables can be derived for arbitrary survey parameters, or alternatively for a number of pre-set values corresponding to planned surveys and experiments. The code also provides forecasts for future cosmological surveys, by allowing the user to compute, manipulate and combine Fisher matrices. The code is written in the IDL language and thus benefits from the simple syntax, large scientific libraries and convenient interactive plotting environment of this language. In particular, all the above calculations can be completed in only a few lines of code.

The code is freely available at \textit{http://www.icosmo.org} with full documentation and help files. It is part of the Initiative for Cosmology website, a global archive for cosmological resources. An interactive web interface to iCosmo is also available at this website (see description in Kitching \& et al.\textsuperscript{2008}).

In this paper, we describe the main features of iCosmo and provide a number of examples illustrating its use. In section\textsuperscript{2} we describe the main conventions and architecture of the code. In section\textsuperscript{3} we describe how the code can quickly calculate the evolution of the basic cosmological quantities, such as distance measures and growth factor, as a function of redshift. In section\textsuperscript{4} we describe how iCosmo calculates the observables for several cosmological probes such as weak lensing, BAO and supernovae. Section\textsuperscript{5} shows how the code can compute and manipulate Fisher matrices. Our conclusions and possible future developments are presented in section\textsuperscript{6}. 


2. General presentation

The iCosmo code is a package of routines written in the IDL language. It is divided into several directories corresponding to the different levels of the calculations:

- general, plotting: general utility and plotting routines.
- cosmo, expt: routines to define fiducial cosmological and survey parameters and compute basic cosmological quantities.
- lensing, bao, sne: routines to compute weak lensing, BAO and supernovae observables.
- fisher: routines to create and manipulate Fisher matrices for cosmological forecasts.

The routines in each of the directories make use of the variable structures in IDL. Their functionality is indicated by the first few letters of their name with the following conventions:

- set: set up basic structures with calculation variables
- mk: make or compute a new structure using the information in an input structure
- get: get a substructure or derived quantity from an existing structure
- plt: plot
- rd, wt: read and write data from and into a file

A description of the main iCosmo routines and associated directories can be found in table[1]. Detailed explanations about any of the routines can be obtained by typing iCosmoHelp, ‘routine name’ at the IDL command line. A readme file is available in the distribution and gives installation instructions and a quick start tutorial.

Table[2] shows an example of a typical call sequence for iCosmo, with the different levels of the code separated with horizontal lines. The following sections describes the use of each levels of the code using examples of call sequences and output figures.

3. Basic cosmological quantities

The first level in iCosmo defines the cosmological model and computes basic cosmological quantities (see e.g. Peacock (1999) for their definitions, and Refregier et al. (2004) for conventions). The first step is to define the fiducial parameter structure using the set_fiducial function (see Inst. 1 in Table[2]). The resulting fid structure contains the following three substructures, which contain the following information:

- cosmo: input cosmological parameters
- expt: experiment parameters, such as survey area, number of galaxies or SNe as a function of redshift, or pre-set surveys.
- calc: calculation parameters, such as redshift and k-range, fitting functions, etc.

These parameters have default values which can easily be modified using the syntax of instruction 1 in Table[2].

The next step is to compute all the basic cosmological quantities using the mk_cosmo function (see Inst. 2 in Table[2]). The resulting cosmo structure is organised into several substructures:

- const: all original fiducial quantities as well as constant quantities derived from the fiducial parameters (e.g. the Hubble radius)
- evol: Evolving scalar quantities such as distance measures, the growth factor, etc, tabulated as a function of redshift
- pk: Linear and non-linear matter power spectrum $P(k, z)$ tabulated as a function of wavenumber $k$ and redshift $z$

The evolving scalar quantities can then be easily plotted using the plt_cosmo routine (see Inst. 3 in Table[2]). As an example, the following call sequence

```idl
fid=set_fiducial(cosmo=[w0:-0.9],calc=[fit,tk:1])
cosmo=mk_cosmo(fid)
plt_cosmo,cosmo,'z', 'da'
```

produces Figure[1] which shows the angular diameter distance $D_A(z)$ as a function of redshift $z$. The fiducial cosmology is $(h = 0.7, \Omega_m = 0.045, \Omega_k = 0.3, \Omega_\Lambda = 0.7, w_0 = -0.95, w_a = 0.0, n = 1.0, \tau = 0.09, \sigma_8 = 0.8)$, unless otherwise stipulated. For example, the call sequence above changes $w_0$ to -0.9, which is used in the rest of this paper.

The plotting routine plt_pk can be used to plot the power spectrum $P(k, z)$ as a function of wavenumber $k$ at a redshift $z$. For example, Figure[2] shows the linear and non-linear power spectrum at $z = 0$ and 1 and is produced by the additional sequence

```idl
plt_pk,cosmo,z=0,xran=[0.001,10.]
plt_pk,cosmo,z=0,/over,/linear,linestyle=2
plt_pk,cosmo,z=1,/over,color=2
plt_pk,cosmo,z=1,/over,linear,linestyle=2,color=2
```

Note that the keyword over can be used to overlay several results on a single figure.

4. Cosmological observables

The next level of iCosmo consists of the calculations of the observables related to different cosmological probes. At present, weak lensing, baryon acoustic oscillations and supernovae are supported. The former probe is implemented using shear power spectrum tomography as described in Hu & Jain (2004); Refregier et al. (2004), Amara & Réfrégier (2007). For BAO, radial and tangential distance scales, along with their errors are derived from the Blake et al. (2006) fitting formulae. We calculate

![Fig. 1. Example of an iCosmo output showing the angular-diameter distance $D_A(z)$ as a function of redshift. The plot was derived using the plt_cosmo routine. See text for command sequence.](image-url)
Table 1. Main iCosmo routines.

| Directory | Routine                  | Description                                      |
|-----------|--------------------------|--------------------------------------------------|
| cosmo     | set_fiducial(cosmo_in=[omega,m:0.31]) | Create fiducial parameter structure              |
|           | mk_cosmo                | Compute basic cosmological quantities             |
|           | get_pk                  | Extract 3D power spectrum                        |
| expt      | mk_survey               | Compute survey parameters                        |
| lensing   | mk_cl_tomo              | Compute lensing power spectrum                   |
|           | mk_cl_cov_tomo          | Compute covariance errors                         |
|           | mk_fisher_lens          | Compute weak lensing Fisher matrix and errors     |
| bao       | mk_bao                  | Compute BAO distance measures                     |
|           | mk_bao_cov              | Compute BAO covariance errors                     |
|           | mk_fisher_bao           | Compute BAO Fisher matrix and errors              |
| sne       | mk_sne                  | Compute SNe magnitude-redshift relation           |
|           | mk_sne_cov              | Compute SNe covariance errors                     |
|           | mk_fisher_sne           | Compute SNe Fisher matrix                         |
| fisher    | check_matrix            | Check matrix is positive definite                 |
|           | comb_fisher             | Combine two Fisher matrices                       |
|           | margin_fisher           | Marginalise over unwanted parameters             |
| plotting  | plt_cosmo               | Plot cosmology parameters                         |
|           | plt_pk                  | Plot 3D matter power spectrum                     |
|           | plt_sv                  | Plot survey properties                            |
|           | plt_cl                  | Plot weak lensing correlation function            |
|           | plt_bao                 | Plot BAO distance measures                        |
|           | plt_sne                 | Plot SNe magnitude-redshift relation              |
|           | plt_fisher              | Plot Fisher matrix errors                         |
|           | plt_fisher_client       | Plot Fisher matrix errors (combined 1D and 2D errors) |
|           | plt_fisher_1p           | Plot 1D likelihood errors                         |
|           | plt_fisher_2p           | Plot 2D error ellipses                            |

Table 2. Example of a typical call sequence for iCosmo. The different levels of the code are separated by horizontal lines.

| Instruction | Description                                      |
|-------------|--------------------------------------------------|
| 1           | fid=set_fiducial('DUNE',expt_in=[sv1,nzbin:2])   |
| 2           | cosmo=mk_cosmo(fid)                              |
| 3           | plt_cosmo.cosmo,'z', 'da'                        |
| 4           | plt_pk.cosmo.z=0                                 |
| 5           | sv=mk_survey(fid,'sv1')                           |
| 6           | cl=mk_cl_tomo(fid,cosmo,sv)                      |
| 7           | cl_cov=mk_cl_cov_tomo(fid,cl,sv)                 |
| 8           | plt_cl.cl,[0,0],cl_cov,errors                   |
| 9           | fish=mk_fisher_lens(fid,sv)                     |
| 10          | margin_fisher,fish,fish2,[0,1,1,0,0,0,0,0]       |
| 11          | plt_fisher_2p,fisher2                           |
| 12          | cl_cov=mk_cl_cov_tomo(fid,cl,sv)                 |
| 13          | plt_cl.cl,[1,1],cl_cov,/errors,yar=1e-7,1e-3     |
| 14          | plt_cl.cl,[0,1],cl_cov,/over,linestyle=1         |
| 15          | plt_cl.cl,[0,0],cl_cov,/errors,/over,linestyle=2 |

The different power spectra correspond to two different tomographic redshift bins with median redshifts 0.68 and 1.36, as well as their cross-power spectra. Similar call sequences can produce predictions and errors for the BAO distance measures and for SNe Hubble diagrams.

5. Fisher Matrices

The final level of iCosmo is related to the computation and manipulation of Fisher matrices to assess the constraints on cosmological parameters that can be achieved with future surveys. For this purpose, Fisher matrices can first be computed using the magnitude-redshift relation for supernovae using the formalism outlined in [Tegmark et al. (1998); Huterer & Turner (2001)] and include both intrinsic scatter and observed variance.

A typical call sequence is given in Instructions 5-8 in Table 2. The sequence first defines the survey using mk_survey and then computes the observable using mk_cl_tomo, mk_bao, mk_sne, for lensing tomography, BAO and SNe respectively. The statistical errors in these observables for the fiducial survey can be derived using the corresponding mk_cov routines listed in Table 1.

As an example, the following produces Figure 3, a plot of weak lensing power spectra for DUNE (Refregier 2008) with its associated 1σ error bars:

```plaintext
> fid=set_fiducial('DUNE',expt_in=[sv1,nzbin:2])
> cosmo=mk_cosmo(fid)
> sv=mk_survey(fid,'sv1')
> cl=mk_cl_tomo(fid,cosmo,sv)
> cl_cov=mk_cl_cov_tomo(fid,cl,sv)
> plt_cl.cl,[1,1],cl_cov,/errors,yar=1e-7,1e-3
> plt_cl.cl,[0,1],cl_cov,/over,linestyle=1
> plt_cl.cl,[0,0],cl_cov,/errors,/over,linestyle=2
```
Fig. 2. Matter power spectrum at $z = 0$ and 1, for top and bottom lines respectively. Linear and non-linear power spectra are shown as dashed and solid lines, respectively. The plot was derived using the pltpk routine.

Fig. 3. The weak lensing power spectrum and associated 1σ error bars for the DUNE weak lensing survey for the first (upper line) and second (middle line) tomographic bins (with median redshifts of 0.68 and 1.36 respectively) as well as the cross-correlation between the bins (lower line).

A typical call sequence to compute and plot fisher matrices can be found in instructions 9-11 in Table 2. As an example, the following sequence computes the fisher matrices for a DUNE weak lensing survey, a half-sky BAO spectroscopic survey (20000 deg^2), and their combination.

```python
⟩ fid_lens=set_fiducial('DUNE')
⟩ fid_bao=set_fiducial('bao_halfsky')
⟩ sv_lens=mk_survey(fid_lens,'sv1')
⟩ sv_bao=mk_survey(fid_bao,'sv2')
⟩ f_lens=mk_fisher_lens(fid_lens,sv_lens)
⟩ f_bao=mk_fisher_bao(fid_bao,sv_bao)
⟩ f_comb=comb_fisher(f_lens,f_bao)
```

The following call sequence produces figure 4 showing the 68%CL constraints on the dark energy parameters $\Omega_{DE}$ and $w_0$ expected for each surveys separately (blue and red ellipse) and jointly (solid green ellipse).

```python
⟩ margin_fisher,f_lens,f_lens2,[0,1,0,0,0,0,0,1]
⟩ margin_fisher,f_bao,f_bao2,[0,1,0,0,0,1]
⟩ margin_fisher,f_comb,f_comb2,[0,1,0,0,0,0,0,1]
⟩ plt_fisher_2p,f_bao2,/nofill,color=2
⟩ plt_fisher_2p,f_lens2,/nofill,linestyle=2,/over
⟩ plt_fisher_2p,f_comb2,/over,color=3
```

The margin_fisher routine was used to retain only the parameters to be plotted, and marginalise over all the other parameters.

Fig. 4. Marginalised 68%CL constraints on the dark energy parameters $\Omega_{DE}$ and $w_0$ expected for the DUNE weak lensing (blue), a full sky BAO survey (red) and their combination (solid green). This figure was derived using the Fisher matrix routines of iCosmo.

6. Conclusions
The iCosmo package provides a convenient and flexible interactive tool to make cosmological calculations and can also be
used as a computation engine in batch mode. Using all the built-in IDL libraries, it is also a convenient platform for the development of further cosmological routines and for teaching. The code, along with an interactive web tool [Kitching & et al. 2008] and various cosmological resources are freely available at http://www.icosmo.org.

In the future, we plan to add a number of features to the code, such as the halo model, higher order clustering statistics, and interfaces with CMB Boltzmann codes. Contributions from the community are encouraged.

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