FOREWORD

This volume presents the proceedings of the GREAT ESF workshop entitled *QSO astrophysics, fundamental physics, and astrometric cosmology in the Gaia era* held on June 6 - 9, 2011 and hosted by the Faculty of Sciences of the University of Porto, Portugal.

The general aim of the meeting, as with all of the GREAT ESF meetings, was a forward look at a class of leading science topics of relevance to the science case, and therefore gauge the relative impact, of a successful Gaia mission, the next European space astrometry initiative.

The subjects addressed by this workshop are perhaps the most intriguing, although less obvious, of the vast science case encompassed by the Gaia survey: the possibility to tackle fundamental physics and cosmology. For, Gaia will not only provide the most complete census of Milky Way objects, it will also, for the first time, chart a large, possibly the largest, all-sky sample of (mostly new) Quasi Stellar Objects (QSOs) in the visible domain; and it will do so by combining accurate astrometry with a five-year-long photometric monitoring. With such an unprecedented net of galactic and extragalactic *fiducial objects* forthcoming, it seemed all the more natural to provide a forum to discuss the most outstanding issues in fundamental physics and experimental gravitation, including probing cosmology at different scales, from the local, i.e. that of the Milky Way, to the large scale of the distant, high redshift, QSOs.

Unlike Hipparcos, Gaia will permit the determination of the extragalactic celestial reference frame directly at optical bands, based on the QSOs with the most accurate positions. Determining this frame will be quite challenging. The state-of-art on the subject was put on the workshop program, so that topics like those following could be addressed: (1) the requirements for such frame, (2) putative future improvements, and (3) the radio counterpart that will be aligned to the Gaia frame.

The comparison of radio and optical positions of QSOs for a large number of such objects is quite relevant for the models that discuss the Active Galactic Nuclei paradigm. If the objects that materialize the celestial reference frame will be those with the most accurate and stable positions (which are therefore critical, defining, properties), there is evidence that flux variations at different time scales, a well known characteristic of QSOs, correlate with variations of the astrometric location of their photocentres. Therefore, photo-centre angular variations at different wavelengths are possibly the results of common phenomena occurring in the vicinity of the central engine of QSOs: the base of relativistic jets, the broad emission line regions, or accretion disks.

A 6-dimensional accurate reconstruction of individual stars across a large fraction of the volume of the Milky Way necessarily needs extremely accurate astrometric observations, which therefore have to be modelled within a fully relativistic framework of, usually higher, accuracy. Then, for a proper formulation of the light trajectory one has to fix the space-time geometry that star light goes through before reaching the observer. In particular, the main gravitational effects acting on the light rays for a local observer are due to the Sun and the Solar System planets, hence the natural choice for the background metric is that adopted by the IAU in 2000. Since General Relativity is the theory needed to build the reference frame at accuracies higher than the milli-second of arc, the astrometric measurements and their link to the relativistic reference frames must be considered. The goal is to understand how (i) to treat gravity properly when

compiling stellar catalogues to micro-second of arc, or μas, accuracy, and (ii) to promote the use of highly accurate astrometry as the most *direct* means to test locally current cosmological models and to help scrutinize, from among several alternative theories, that providing the route to quantum gravity.
In fact, high precision astrometry of galactic and extragalactic objects provides direct and independent experimental grounds to the most daunting challenges in fundamental physics and cosmology. High accuracy monitoring of the astrometric stability of QSOs at different redshifts can be of paramount importance in observational cosmology: here, the intrinsic astrometric stability of (carefully selected) QSOs is tested to reveal any anisotropy of the Universe, i.e., isotropy deviations due to uneven distributions of dark matter and dark energy or, perhaps, to gravitational waves of cosmological origin.
At the local scale, i.e. dealing with local cosmology, accurate absolute motions of stars within our Galaxy will provide access to the cosmological signatures in the disk and halo as predicated by, e.g., the ΛCDM model. Indeed, the value of accurate kinematics at the scale of the Milky Way is unique in its ability to account *in situ* for the predictions of the cold dark matter model, in the case of the halo, and eventually map out the distribution of dark matter or other alternative formation mechanisms required to explain signatures already identified in the old component of the thick disc.

At the time these Proceedings are sent to press, the launch of Gaia is scheduled for the end of October 2013, on Soyouz launcher no.13 lifting off the new ELS launch facility (the *Ensemble de Lancement Soyouz*) at the *Centre Spatial Guyanais* (CSG), of the European Space Agency, in Kourou.

The interest for the Gaia potential in quasar astronomy was confirmed by the number and quality of the contributions from the radio astronomers and experts in fundamental astronomy. However, if the response related to QSO astrophysics and the astronomy of reference frames (e.g., realization of the ICRF across the electromagnetic spectrum and related connection/alignment issues) was easily anticipated, the high expectations on new discoveries (number, coverage, and distance, up to redshifts of $\lesssim 3$) and on the possibility of detailed optical monitoring down to relatively faint magnitudes, although not unexpected, was certainly a pleasant outcome! Further demonstration of the attention that this scientific community has for the Gaia mission.

The release by ESA of the expected performance for the *as-built* payload, which happened not long before the workshop took place, was what needed to put Gaia in context, allowing the participants to enter into a more detailed evaluation of the actual impact that Gaia will have on their research programs. The discussions that ensued highlighted how the *end-of-mission* 10-200 μas (magnitude dependent) astrometric accuracy range expected on QSOs will indeed be a revolution for relativistic reference frame realization and materialization, with the main limitation coming for those programs requiring astrometric monitoring throughout the mission. For, *time-resolved* astrometry will be $\sim$ 10 to 30 times worse for a single field-of-view crossing or a transit over a CCD unit, respectively. This means that the astrophysical and, potentially, cosmological value of Gaia's astrometric monitoring on the fainter (and for the large part newly discovered) QSOs might be somewhat diminished. In particular, it remains to be established if Gaia will be able to contribute significantly in uncovering possible transient astrometric events like quasar "trembling", possibly associated to distortions in the space-time fabric caused by cosmological gravitational waves.

Unquestionably, the conference established that Gaia will signify the beginning of *astrometric cosmology*. Its measurements of the expected cosmological signatures in the main components

of the Milky Way, halo and thick disc, will be unique and unprecedented in quality and quantity, to the point that they will constitute direct observational evidence to which theories will have to confront. Here, the 10 μas floor in the astrometric error does not appear as a limitation; this comes rather from the operational wavelengths that do not allow optimal charting of the galactic plane, where an infrared version of Gaia would have helped greatly.

Advanced discussions on the contributions to the physics of gravitation revealed that full testing of alternative theories of gravity does require to push for the 1-μas astrometric accuracy and possibly beyond. Besides these limitations, Gaia will nevertheless realize the most accurate and sophisticated large-scale experiment in experimental gravitation ever attempted; and this by using astrometry, the same direct technique that only a century ago decreed the triumph of Einstein's General Relativity.
In this framework, detailed and realistic *technical* plans that bear the promise to achieve a factor of ten or more improvement in astrometric accuracy were also debated, therefore setting the scientific and technological scenario for a *beyond Gaia* that was presented to the attention of ESA and the other major space agencies for future consideration toward new initiatives in space astrometry.

We hope the interested readers, experts or researchers new to this field of investigation, will find this volume not only useful, but as stimulating and enriching as the days of the workshop were for us. For this, we can only thank the colleagues that took the time to put their contributions on paper, thus making this volume a reality.

Finally, it is our pleasure to thank the Editor of the *Memorie della Società Astronomica Italiana*, Dr. Bonifacio, and his Scientific Advisory Board for kindly accepting to publish the contents of our conference in their Journal.

The editors and organizers,

S. Antón, M. Crosta, M. G. Lattanzi & A. Andrei