Mem. S.A.It. Vol. 83, 1077

Memorie della

Gravitation Astrometric Measurement Experiment

M. Gai, A. Vecchiato, S. Ligori, and A. Riva

Istituto Nazionale di Astrofisica – Osservatorio Astronomico di Torino, Via Osservatorio 20, I-10025 Pino Torinese (TO), Italy, e-mail: gai@oato.inaf.it

Abstract. The Gravitation Astrometric Measurement Experiment (GAME) mission concept takes advantage of astronomical techniques, also inherited from Gaia, for high precision measurements of the γ and β parameters of the Parameterized Post-Newtonian formulation of gravitation theories extending General Relativity. A space based telescope, looking close to the Solar limb thanks to corona-graphic techniques, may implement astrometric measurements similar to those performed in the solar eclipse of 1919, when Dyson, Eddington and Davidson measured for the first time the gravitational bending of light. Simulations show that the final accuracy of GAME can reach the 10^{-8} level on γ and the 10^{-6} level on β within the framework of a medium class space mission. The GAME principle is based on the differential astrometric signature on the positions of stars and planets. The concept ensures rejection of the systematic errors to within a factor 2 of the photon noise limit.

1. Introduction

The observation of known stellar fields during an eclipse (May 29th, 1919) by Dyson, Eddington and Davidson gave the first confirmation of Einstein's General Relativity theory. They measured the apparent positions of a few stars during the eclipse, within a few degrees from the solar limb, with respect to their unperturbed relative positions. The arc variation was interpreted in terms of light deflection, providing an estimate of the γ parameter with precision $\sim$ 10%, i.e. to a 10^{-1} accuracy estimation of the PPN γ parameter. Measurements of light deflection from the ground are affected by many shortcomings: short eclipse duration, high background flux from the solar corona, atmospheric disturbances and the limited number of bright sources in the field, thus limiting the achievable performance.

The main science goal of GAME is the estimation of key parameters of the Parametrized Post-Newtonian formalism (Will 2006), commonly used to test the weak-field limit of metric theories of gravity in the Solar System. The focus is on Eddington's parameters, γ, to a few 10^{-8}, and β, to a few 10^{-6}. The current best estimate of γ, from the Cassini experiment, is in the 10^{-5} range (Bertotti et al. 2003). The β parameter was estimated to a few 10^{-4} thanks to accurate orbit determination of Solar System bodies (Fienga et al. 2009) evidencing the effect of perihelion shift excess, similarly to the historical case of Mercury.

The possibility of testing gravity theories to this accuracy has deep implications for our understanding of several fundamental physical and astrophysical issues. GAME can also pro-

Send offprint requests to: M. Gai

vide crucial information on several other issues of Solar System (in particular Near Earth Object orbit determination), extra-solar planetary systems, stellar astrophysics and high angular resolution monitoring of the Corona and circumsolar environment.

2. Estimation of γ

The Parametrised Post-Newtonian (PPN) formalism (Will 2006) was introduced to classify metric theories of gravitation, in their Post-Newtonian limit, through a set of parameters. The γ parameter quantifies the effect of mass on space-time curvature, while β is related to the superposition non-linearity for the gravity fields of different bodies; in General Relativity (GR) $\gamma = \beta = 1$. GR acts as a cosmological attractor for scalar-tensor theories of gravity, with expected deviations on γ in the 10^{-5}–10^{-7} range.

Besides, there is observational evidence for an accelerated expansion of the Universe. This was interpreted, in the concordance ΛCDM scenario, as the effect of a long range perturbation to the gravity of the visible matter, generated by the so-called Dark Energy. Other observations at different scale (e.g. galaxy rotation curves) are explained with non-barionic Dark Matter or some kind of GR modification (e.g. Pioneer anomalies).

However, these data might also be explained with a modified version of GR, in which the curvature invariant R in Einstein's equations is no longer constant ($f(R)$ gravity theories). Present experimental data are not accurate enough to discriminate among the options, but this could be done with a $< 10^{-7}$-level measurement of γ (Capozziello and Troisi 2005).

From a phenomenological standpoint, the γ parameter is associated to the light deflection, and it can be shown (Vecchiato et al. 2009) that the accuracy on γ is proportional to that on the light deflection, directly related to the measurement precision of the angular separation.

The peak value of light deflection is $1''.74$ at the solar limb, and decreases with increasing angular distance. Thus, in order to estimate the γ parameter at the 10^{-6} level and beyond, microarcsec (μas) level measurements of relative star positions are required, at a few degrees from the Sun. Previous simulations showed that the 10^{-7} level of accuracy could be reached within the baseline of this measurement concept, scaled to fit a *small mission* framework (Vecchiato et al. 2009). The 10^{-8} accuracy goal of the *medium mission* GAME version (Gai et al. 2011) comes from improvement factors as the *longer mission duration*, use of *four larger fields of view* (e.g. North, South, East and West with respect to the Sun centre), and an optical configuration designed for *control of systematic errors*. In addition to the four Sun-ward fields, GAME also observes at the same time four ("outward") fields, in the direction opposite to the Sun.

Adoption of a highly symmetrical instrument design mitigates the calibration requirements, as the instrument response is the same, at first order, for all fields. Using the same optical paths and detector, perturbations are expected to act mainly in common mode, reducing their influence on the differential measurement. Observation of selected fields at different epochs modulates the deflection ON (Sun between fields) and OFF (Sun at large distance).

The benefits to systematic error control of simultaneous observation of 2 + 2 or 4 + 4 fields are not only related to *increased efficiency*, but above all to *real time compensation of systematic errors*. The superposition can be achieved with techniques similar to those adopted in Hipparcos and Gaia, i.e. a *beam combiner* (BC) folding onto the same detector the images of the two fields. The separation between observing directions, materialized by the BC, is the *base angle* (BA).

3. The measurement technique and performance

The medium mission version of GAME is based on a 1.5 m diameter telescope, with corona-graphic and multiple field beam combination sub-systems. The satellite is oriented with a side always set within 35° to the Sun, thus simplifying the design of payload thermal control and solar panel allocation; the detector

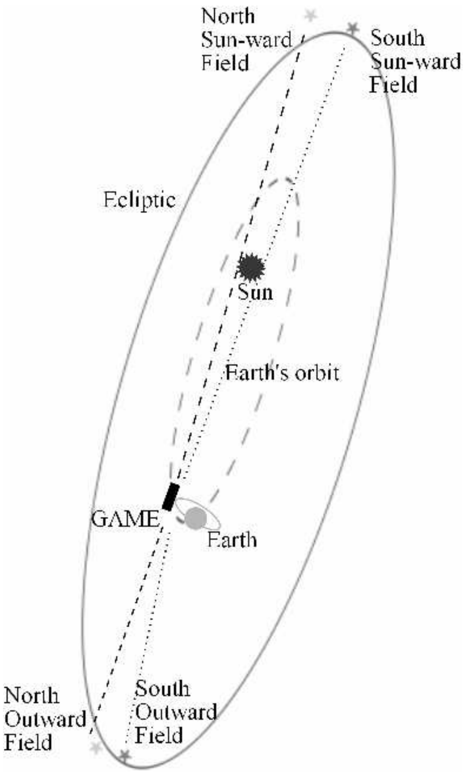

Fig. 1. The GAME satellite observing stellar fields close to the Sun and in the opposite direction.

radiator is naturally set on the dark side. The telescope is endowed with a pupil mask and a folding mirror for injection of the out-ward field beams. Each sub-aperture acts as a coronagraph for rejection of the Sun disk at the $R \leq 10^{-8}$ level, and of the inner Corona, whereas, with respect to the stellar fields, the set of sub-pupils works as a Fizeau interferometer, feeding the underlying monolithic telescope. The Fizeau interferometry concept achieves a convenient trade-off between the angular resolution needed for precision astrometry (image FWHM $<$ 100 mas), and corona-graphic requirements, applied to each small aperture defined by the pupil mask on the underlying telescope. The background is limited by the Corona, at 2° from the Sun centre, to $\sim$ 9 mag per square arcsec.

GAME observes in step-and-stare mode four fields around the Sun, at 2° from the Sun centre (deflection: $\sim$ 0$''$.233). In addition to the four "Sun-ward" fields, GAME also observes at the same time, and using as much as possible the same parts of the instrument, four "outward" fields with the same relative placement in the direction opposite to the Sun. Subsequent exposures of the superposed fields are taken, to compute the photo-centre location of each star image in deflection ON and OFF epochs. The photo-centre displacement provides an estimate of the angular value of light deflection, which can then be averaged over the star sample. Relaxed requirements are imposed on a priori knowledge of star parameters and on pointing accuracy; accurate reconstruction of attitude and sample astrometry is expected from the data processing.

The measurement scheme of GAME is *fully differential*, based on determination of the variation between epochs of the angular distance between stars in selected fields. The measurement noise performance (random error) depends on the location precision on individual sources, and on the total number of sources. The expected noise limit of GAME on γ in the five years mission lifetime is $\sigma(\gamma)/\gamma = 2.8 \times 10^{-8}$. A further 30% degradation, associated to uncalibrated systematic errors, is introduced, resulting in a realistic performance estimate of $\sigma(\gamma)/\gamma = 3.8 \times 10^{-8}$.

A simple estimate of the precision on β by reconstruction of Mercury's orbit results in $\sigma(\beta)/\beta \simeq 5 \times 10^{-6}$).

4. Conclusions

The smart combination of modern astrometric and coronagraphic techniques allows the definition of a mission concept able to provide unprecedented results on Fundamental Physics through estimation of the PPN parameters γ and β, respectively to the 10^{-8} and 10^{-6} range.

The GAME concept can also be implemented as a small mission operating for just two years, with performance expected to decrease by only one order of magnitude.

References

Bertotti, B., Iess, L., Tortora, P. 2003, Nature 425, 374

Capozziello, S., Troisi, A. 2005, Phys. Rev. D 72(4), 044

Fienga, A., et al. 2009, A & A, 507, 1675

Gai, M., Vecchiato, A., Ligori, S., Lattanzi, M.G. 2011, Exp. Astron. vol. 34, 165180

Vecchiato, A., Gai, M., Lattanzi, M.G., Crosta, M., Sozzetti, A. 2009, Adv. Space Res. 44, 579

Will, C.M. 2006, Living Rev. Relativity, 9(3)