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Memorie della

Gamma Astrometric Measurement Experiment

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Abstract. GAME aims at the measurement of gravitational deflection of the light by the Sun, by an optimised telescope on board a small class satellite. The targeted precision on the γ parameter of the Parametrised Post-Newtonian formulation of General Relativity is below 10^{-6}, i.e. one to two orders of magnitude better than the best current results. Such precision is suitable to detect possible deviations from the unity value, associated to generalised Einstein models for gravitation, with potentially huge impacts on the cosmological distribution of dark matter and dark energy. The measurement principle is based on differential astrometry. The observations also allow additional scientific objectives related to tests of General Relativity and to the study of exo-planetary systems. The instrument concept is based on a dual field, multiple aperture Fizeau interferometer, observing simultaneously two regions close to the Solar limb. The diluted optics achieves efficient rejection of the solar radiation, with good angular resolution on the science targets. We describe the science motivation, the proposed mission implementation and the expected performance.

Key words. Gravitation – Relativity – Space vehicles: instruments – Astrometry – (Cosmology:) cosmological parameters – Instrumentation: interferometers

1. Introduction

The bending of the light path due to the gravitational pull of massive bodies (Fig. 1) is one of the best known effects introduced by the General Theory of Relativity (GR). In the GR language, the effect is interpreted in terms of the curvature induced on the space-time geometry by the mass of the bodies. The PPN formalism (Will 2006) identified a whole class of metric theories of gravity each characterised by the values of a given set of parameters. Here, the γ parameter quantifies the effect on space-time curvature; $\gamma = 1$ in GR.

The Gamma Astrometric Measurement Experiment (GAME) is a novel implementation, a century later and with modern technology, of the experiment of Dyson, Eddington and Davidson, which gave in 1919 the first confirmation of Einstein's GR theory. It was based on relative position measurement for a few stars, both close to the solar limb (during an eclipse) and quite away from the Sun (in night time, at different epoch); the position variation provided the measurement of light deflection to an accuracy on γ limited to 10%. The limit was due to short eclipse duration; high background flux from the solar corona; atmospheric disturbances; limited number of bright sources in the field on a given eclipse. The same technique was used several times in the following decades (Vecchiato et al. 2006), but the accuracy did not improve much, basi-

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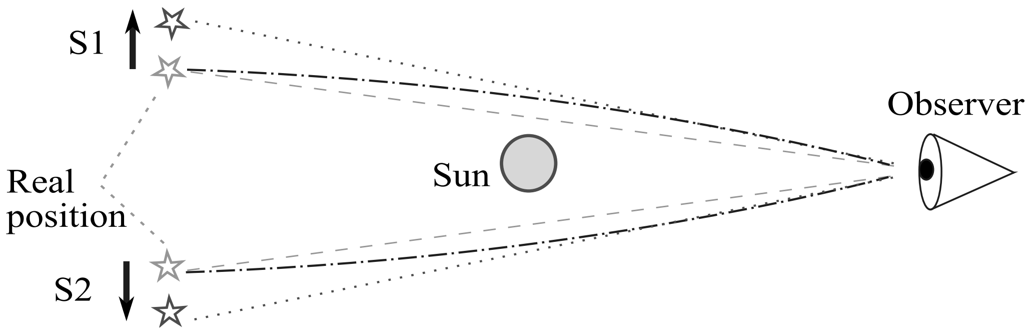

Fig. 1. Representation of the apparent effect of light deflection by the Sun. The unperturbed direction (dashed lines) of stars S1, S2 as seen by the observer is modified by the presence of a massive body bending the photon trajectories (dash-dotted line), generating apparent new positions corresponding to the geometric prolongation of the arrival direction (dotted line). The angular separation of the stars S1, S2 thus changes with time according to their position with respect to the Sun.

cally due to the same experimental limitations. We propose the implementation of a similar experiment in space, getting rid of the atmospheric turbulence, with an instrument able to generate its own artificial eclipse, thus observing for long periods selected sources. The precision goal of GAME on γ is in the range $10^{-6} - 10^{-7}$, i.e. one–two orders of magnitude better than the best current results from alternative techniques: 10^{-4} to 10^{-5} from the Viking, VLBI and Cassini data (Bertotti et al. 2003). The GAME measurement is fully differential, relying on the astrometric signature on stellar positions. It is based on the spatial rather than the temporal component of the effect, as in the experiments using radio link delay timing. The measurement conditions of the two experiment classes are independent, providing a convenient framework for mutual verification. In this paper, we describe the science drivers of GAME (Section 2), leading to the main instrument and operation specifications, the key implementation concepts and the expected performance (Section 3).

2. Science case

The goal of GAME may be achieved by accurately measuring the relative positions of many stars in two different fields in the vicinity of the Sun, thanks to a suitable beam combiner splitting and folding the line of sight of a telescope in the two desired directions; the two field images are superposed onto the common focal plane detector. The Sun lies between the two observing directions, out of the fields of view; a baffling system generates an artificial eclipse. By measuring the difference in relative star position at two epochs, i.e. when the Sun is either between the two fields or far away, we derive the starlight deflection related to γ. Deviations from the GR value are associated to generalised Einstein models for gravitation, e.g. the $f(R)$ theories (in the range 10^{-5} to 10^{-7}), with potentially huge impacts on the cosmological distribution of dark matter and dark energy, which might be replaced, partially or totally, by space-time curvature effects justifying the same observed effects (Capozziello and Troisi 2005). GAME builds on astrometric measurement well established in the ESA missions HIPPARCOS and Gaia, but it adopts a fully differential scheme (Gai et al. 1999) optimised for the determination of γ. A small mission, observing repeatedly selected sky regions close to the ecliptic, can provide the desired precision. We are studying a payload design and mission profile able to achieve 10^{-6} relative precision of γ.
Some of the authors investigated the achievable performance of γ determination by astrometric measurements from the Gaia mission (Vecchiato et al. 2003), evidencing a photon-limited precision close to the goals of GAME.

The simulation assumed simply an overall envelope of systematic and calibration errors. However, for Gaia, γ is just one among several million astrophysical parameters, and many thousand of instrumental ones, derived from the whole set of observations taken through the five year mission lifetime. With GAME (Vecchiato et al. 2007), the same photon limited result is achieved with about two months of observations, with nearly simultaneous calibration. The final result can be further improved by averaging down the measurements, as far as systematic errors do not become the limiting factor.

Observations close to the limb of Jupiter or Saturn will provide estimates of the light deflection induced by the quadrupole component of their gravitational field. The possibility of measuring this $\sim$ 240 micro-arcsecond (μas) effect, foreseen by GR but still never addressed by any experiment, has been simulated for a Gaia-like mission for the first time in Crosta and Mignard (2006), and led to a specific project (GAia Relativistic EXperiment, or GAREX) in Gaia. The GAREX concept is applicable to GAME with significant advantages in the observing flexibility, allowing to assess the detection of the quadrupole effect by including all the gravito-dynamical relativistic terms due to the orbital velocity of the planet.

GAME will also be able to provide high precision astrometric and photometric measurements for a number of astrophysical goals, from orbital analysis of known exo-planets, to monitoring of comets and near-Earth asteroids in the most internal part of their orbit. In particular, the subject of mass of planets and brown dwarfs, and that of timing of exo-planet transit by photometric monitoring, may be addressed. Besides, high resolution observations close to the Sun limb can provide information on transient corona phenomena.

3. GAME payload implementation

The instrument concept is a dual field, multiple aperture Fizeau interferometer, with line of sight folded on two sky regions by a beam combiner (BC), built by aperture masking of a telescope. The diluted optics approach shall provide an efficient rejection of the scattered solar radiation, while retaining sufficient angular resolution on the science targets. The measurement of the arc between stars corresponds to determination of the fringe pattern phase.

The combination on the telescope line of sight of the fields from two directions on the sky is performed by the beam combiner (BC), an assembly of two flat mirrors, set at a fixed angle. Each half pupil of the telescope images the field of view around the observing directions set by the BC. The simple BC approach was successfully used by the ESA mission Hipparcos, mounting the two halves of a mirror at a tilted angle. The concept can be retained for GAME, at least in principle. The BC must be stable during the measurement sequence; its variation is indistinguishable from the displacement due to the gravitational deflection. An on-board metrology system is considered, to complement the on-sky calibration.

The telescope optical design is not critical; further optimisation is aimed mainly at improving the overall instrument robustness with respect to optical component manufacturing, tolerancing and alignment errors; baffling efficiency; convenient payload allocation in terms of geometry, mass budget, and stability. The set of individual apertures on the telescope pupil produces a fringed image. All apertures contribute to a coherent diffraction image with resolution comparable to the full edge to edge size of the underlying telescope. Each aperture can be individually baffled, even on the short length of the payload envelope.

The preliminary optical configuration (Loreggia et al. 2007) has been implemented in the ray tracing package Code V. Each of the five rectangular apertures for each line of sight is 60×150 mm, resulting in an external diameter of 0.62 m. The effective focal length is 21 m; the fringe visibility is $> 95\%$ over a field of 7×7 arcminutes. The distortion is low, resulting in a relative scale variation $< 10^{-4}$. Observing close to the Sun, high efficiency rejection of solar photons is required. The proposed diluted optics solution allows baffling of individual apertures, fed by the pupil mask through a path length ~ 4 m. The ratio of aperture size to mask distance is $1/67$.

The preliminary satellite definition is based on a previous spacecraft, adapted for the GAME instrument, with a payload mass budget of 300 kg. The planned mission lifetime is two years, with a possible mission extension of two additional years. The elevation of 1500 km, and a polar, Sun-synchronous orbit with proper inclination, avoids eclipses.

The precision on the GAME measurable, i.e. the separation between stars in the field, derives from composition of the results from the location process applied on each individual source. The star location error is derived by least square methods (Gai et al. 1998, 2001). The performance vs. source magnitude was derived for a diffused background of 15.5 mag and 19.75 mag per square arcsecond, respectively with an exposure time of 100 s and 500 s. The former case represents the background level close to the Sun, whereas the latter refers to measurements at large angular distance to the Sun, e.g. in calibration or low deflection epoch. The longer exposure time is most convenient for the additional science cases (e.g. deflection close to Jupiter's limb). The detector quantum efficiency is assumed to be 70%; the spectral bandwidth has $FWHM = 120$ nm around the central wavelength $\lambda_0 = 650$ nm.
With the shorter exposure time, the elementary exposure error is < 1 mas at magnitude 15.5, and < 0.1 mas at 11 mag. Using the average star counts from the GSCII catalogue, and observing all stars down to 16 mag along the ecliptic, for a period of 20 days, the precision on γ is 3×10^{-6}. Observing sequences set in high stellar density regions further improve the precision to the 10^{-7} level.

4. Conclusions

We discuss a possible implementation of fundamental tests on General Relativity, verifying its predictions on the light deflection by the Sun to a precision range 10^{-6} to 10^{-7}.
GAME is based on a small satellite observing fields on the ecliptic for up to two years; it overcomes the limitations of ground based measures: short duration of natural eclipses, high photon background and astrometric noise from atmospheric turbulence. GAME can also detect the never measured effect of the mass distribution asymmetry (quadrupole moment) on the light deflection around major planets.
GAME is based on a Fizeau interferometer achieved by pupil masking of a telescope, fed by two fields of view through a beam combiner; the optical train also contains the baffling for mitigation of the high photon flux from the Sun.

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