

Can the flyby anomalies be explained by a modification of inertia?

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ABSTRACT

The flyby anomalies are unexplained velocity increases of 3.9, 13.5, 0.1 and 1.8 mm/s observed near closest approach during the Earth flybys of the Galileo, NEAR, Cassini and Rosetta spacecraft. Here, these flybys are modelled using a theory that assumes that inertia is caused by a form of Unruh radiation, modified by a Hubble-scale Casimir effect. This theory predicts that when the craft's accelerations relative to the galactic centre approached zero near closest approach, their inertial masses reduced for about 10^{-7} s causing Earthward jumps of 2.6, 1.2, 1.4 and 1.9 mm/s respectively, and, to conserve angular momentum, increases in orbital velocity of a few mm/s that, except NEAR's, were quite close to those observed. However, these results were extremely sensitive to the Hubble constant used. As an experimental test of these ideas, it is proposed that metamaterials could be used to bend Unruh radiation around objects, possibly reducing their inertial mass.

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1 Introduction

Several large-scale dynamical anomalies remain unexplained, including: 1) the galaxy rotation problem noticed by Zwicky (1933) in which the stars in galaxies are too energetic to be bound by standard theories of gravity, 2) the Pioneer anomaly discovered by Anderson *et al.* (1998) in which the Pioneer craft seem to be attracted to the Sun slightly more than expected and 3) the flyby anomalies described by Antreasian and Guinn (1998) and Anderson *et al.* (2006) in which some spacecraft during gravity assist flybys have shown anomalous velocity jumps of a few mm/s. These problems can all be interpreted as unexpected increases in gravitational interaction (either an increase in Newton's gravitational constant G , an increase in gravitational mass, or a loss of inertial mass), and the first two anomalies appear at very low accelerations (of the order of $10^{-10}ms^{-2}$).

An increase of G for such low accelerations is the approach of some versions of MOND (MODified Newtonian Dynamics), an empirical theory introduced by Milgrom (1983) to solve the galaxy rotation problem. The problem with this approach is that it does not explain why the Pioneer craft and the planets behave differently. An increase of gravitational mass is the approach of the popular dark matter hypothesis of Zwicky (1933). However, it is possible to fit dark matter distributions to solve the problem, but no theory yet exists to explain the distributions. It is also difficult to explain the Pioneer anomaly using dark matter since, again, the planets would also be effected.

The third approach: reducing the inertial mass for low accelerations, was suggested by Milgrom (1999) who realised that MOND could be interpreted this way. As he noted, there are observations that imply that it is inertia that should be modified. For example: the possible change in behaviour of the Pioneer craft upon moving from a bound to an unbound trajectory (to be confirmed, or not, soon, by the Pioneer team, see Toth and Turyshev, 2006), and the planets, which are on bound orbits, do not seem to show the anomaly. A modification of inertia is the only approach that can be made to depend upon trajectory, as this phenomenon appears to. The problem with this approach is that it violates the equivalence principle. However, as noted by McGaugh (2007) this principle has not been tested at very low accelerations, which are difficult to attain on Earth.

A possible model for modified inertia can be found by starting from the

work of Haisch *et al.* (1994) who suggested that the inertial mass of a body is caused by a drag from a form of Unruh radiation (Unruh, 1954) which is only apparent upon acceleration. Since the wavelength of this radiation lengthens as the acceleration reduces Milgrom (1994, 1999) suggested that there would be a break in this quantum vacuum effect and a consequent loss of inertia for very low accelerations when the Unruh wavelengths exceed the Hubble distance showing behaviour similar to MOND, though the behaviour for intermediate accelerations, like that of the Pioneer craft, was undefined. McCulloch (2007) proposed a model which could be called Modified Inertia due to a Hubble-scale Casimir effect (MiHsC), in which, as the acceleration reduces the radiation is diminished linearly since fewer wavelengths fit within twice the Hubble distance, a more gradual process than Milgrom’s break. In this model, the equivalence principle ($m_i=m_g$) becomes

$$m_I = m_g \left(1 - \frac{\beta \pi^2 c^2}{a \Theta} \right). \quad (1)$$

where m_I is the modified inertia, m_g is the mass of the spacecraft, $\beta = 0.2$ (from the empirically-derived Wien’s constant), c is the speed of light, Θ is twice the Hubble distance $2c/H$, and a is the acceleration of the craft relative to the galactic centre. This model agreed with the Pioneer anomaly beyond 10 au from the Sun without the need for adjustable parameters (McCulloch, 2007). However, the model also predicted an anomaly within 10 au, where none was observed (MiHsC may not be applicable to bound trajectories).

During four Earth gravity assist flybys, anomalous velocity increases of a few mm/s were observed near closest approach (Antreasian and Guinn, 1998, Anderson *et al.*, 2007) and these are known as the flyby anomalies. Table 1 lists the spacecraft involved (column 1), the flyby dates (column 2) and the anomalous velocity increase seen (dV, column 3). So far, no explanations for these events have been found (Anderson *et al.*, 2007).

It may seem that the flyby anomalies are unlike the galaxy rotation problem and the Pioneer anomaly, because the accelerations involved are larger. However, Ignatiev (2007) suggested that small short-lived zones of modified inertia could occur on Earth, under very rare conditions in which the *total* acceleration relative to the galactic centre approached zero. It is reasonable to ask whether this occurs for near-Earth objects too. In this paper

the flybys are modelled using the version of modified inertia suggested by McCulloch (2007), in an attempt to explain the flyby anomalies.

Mission	Flyby date	Observed dV (mm/s)
Galileo	8/12/90	3.92 ± 0.08
NEAR	23/1/98	13.46 ± 0.13
Cassini	18/8/99	0.11
Rosetta	4/3/05	1.82 ± 0.05

Table 1: Observed flybys with good data (Anderson *et al.* 2007, Lämmerzahl *et al.*, 2006). The error bars are also shown, where known.

2 Method

Ephemeris data for the Earth, Moon and the spacecraft, for each of the four flybys were downloaded at 1 minute temporal resolution from the excellent JPL Horizons website for the dates shown in table 1, column 2. The spacecraft trajectories were then modelled using Newtonian dynamics and MiHsC.

A starting point along the trajectory about 1 hour before closest approach was chosen and the model was initialised with the position and velocity data from JPL at that point and then run for six hours with a time step of 0.2 s. This time step was increased to $O(10^{-7}s)$ during the time-step within which the acceleration passed through zero to better resolve the decrease in inertial mass predicted by equation (1). During this sub-model phase the acceleration was forced to remain above $6.9 \times 10^{-10}ms^{-2}$ since in MiHsC the acceleration cannot pass below this minimum value. This is because for very low accelerations the inertial mass reduces, and this increases the acceleration again. An equilibrium is established at this value (see McCulloch, 2007). The numerics were handled using a simple forward-stepping scheme. The value used for the Hubble constant was $2.33 \times 10^{-18}s^{-1}$. In McCulloch (2007) the value used was $2.3 \times 10^{-18}s^{-1}$. This difference is discussed below.

The inertial masses of the Earth, Moon, Sun and spacecraft were not altered in this simulation because it was assumed that bound orbits do not show an

anomalous effect, using the example of the Pioneer craft which did not appear to show an anomaly while bound to the Sun (to be confirmed, or not, soon: see Toth and Turyshev, 2006) and the planets, which, of course, do not show an anomaly.

Figures 1-4a (the top left plots) show the trajectories for each of the flybys looking down on the Earth's north pole. In each plot the Earth's trajectory is in bold, the moon's is lighter and the spacecraft's is shown lighter still and shows a change in direction near close approach due to the Earth's gravity.

3 Results

Figure 1 shows the results for the Galileo flyby which occurred on the 8th of December, 1990. As discussed above the top left plots show the trajectories. The bottom left plot shows the heliocentric spacecraft velocity (see the upper curve and the left hand axis). The peak velocity occurred about one hour into the run at closest approach, and was about 37 km/s in this case. Note that the final velocity is greater than the initial, because this flyby added momentum to the craft. The bottom curve shows the total acceleration of the craft relative to the Sun (the axis is on the right). Ideally, the acceleration of interest is that relative to the galactic centre (GC), but the Sun's acceleration relative to the GC is very small: about $10^{-10}ms^{-2}$, so an origin at the Sun should suffice. Near closest approach the acceleration passed close to zero, an event which reduces the inertial mass according to equation (1). The inertial mass is shown by the thicker horizontal line and its axis is on the right. The predicted reduction of inertial mass can be seen as a vertical spike. It reduced from 2497 kg to 2.1 kg, but over a duration of only $3 \times 10^{-7}s$. The negative spike in inertial mass seen here is similar to the SHLEM (Static High Latitude Equinox Modified inertia) effect predicted to occur on Earth on very rare occasions by Ignatiev (2007).

The predicted reduction in inertial mass caused an increase in the acceleration towards the Earth and an Earthward velocity jump of 2.6 mm/s (see Table 2, column 3). To conserve angular momentum the orbital velocity then increased. The predicted anomalous increase in heliocentric velocity is shown by the solid line in the top right plot and the anomalous geocentric velocity is shown by the dotted line. As the craft jumped towards the Earth

exchanging momentum with it, its geocentric velocity decreased briefly, but the extra orbital velocities increased quickly to about 2-3 mm/s and thereafter increased ever more slowly. They were still rising slightly after 6 hours, but the increase of interest is the one that occurs, like the flyby anomalies, near closest approach. The bottom right plot shows the difference in the craft's distance from Earth between the MiHsC and Newtonian runs. In the MiHsC run, the Earthward jump in velocity at first decreased this distance, but the greater orbital velocity eventually leads to a distance anomaly which increases at a rate of 10 m per hour, or about 3 mm/s.

Mission	Observed dV (mm/s)	Predicted Earthward dV (mm/s)	Craft mass (minimum) (kg)	Mass loss duration (s)	Time after C.A. (mins)
Galileo	3.92	2.6	2497 (2.1)	3×10^{-7}	12
NEAR	13.46	1.2	730 (0.6)	0.6×10^{-7}	-2
Cassini	0.11	1.4	4612 (4.0)	2×10^{-7}	7
Rosetta	1.82	1.9	2895 (2.5)	2×10^{-7}	9

Table 2: Column 1: The flyby name, Column 2: The observed orbital velocity jumps. Column 3: the predicted *Earthward* velocity jumps (mm/s). Column 4: the nominal and minimum inertial masses (kg). Column 5: the duration of the mass-loss event (in seconds). Column 6: the times of occurrence of the mass loss event relative to closest approach (in minutes).

The predicted orbital jumps in velocity for all four of the flybys are shown in Figures 1-4 (the top right plots) and summarised in table 2. In the table columns 2 and 3 show the observed orbital and predicted *Earthward* velocity jumps. The predicted orbital velocity jumps are shown in Figures 1-4. The predicted velocity jumps for Galileo and Rosetta agreed quite well with those observed, but that for NEAR was an order of magnitude smaller. Since equation (1) is a difference between two terms, one of which contains the Hubble constant H , these results depended strongly on the value chosen for H which, for these results, was $2.33 \times 10^{-18} s^{-1}$. For a value of $H = 2.3 \times 10^{-18} s^{-1}$ the predicted jumps were less than 1 mm/s and for $H \geq 2.34 \times 10^{-18} s^{-1}$, the jumps were negative since the second term on the right hand side of equation

(1) became dominant. Therefore, this theory succeeds for only a very narrow range of values of H . Column 4 of table 2 shows the gravitational mass (and normal inertial mass) of the craft and, in brackets, the minimum inertial mass achieved during the mass loss event. Column 5 shows the duration of that event. The loss of inertial mass was greatest for the NEAR flyby (it reduced from 730 kg to 0.6 kg), but the duration of the mass loss was shorter. Column 6 of table 2 shows the time, relative to close approach (CA), that the jump (and the mass loss event) occurred. They occurred a few minutes after closest approach (positive values) except in the case of NEAR where the mass loss occurred two minutes before. Unfortunately, the exact timing of the event can not be compared with these results since contact with the craft was lost by the tracking stations near closest approach.

4 An experimental test

If the ideas discussed here are correct then it should be possible to reduce the inertial mass of an object by reducing the Unruh radiation it sees upon acceleration. One way to achieve this could be to use the metamaterials recently devised by Pendry *et al.* (2006), or Leonhardt (2006). They have demonstrated that radiation can be bent around an object that is smaller than that wavelength using a metamaterial, in such a manner that the rays exit the vicinity of the object in the same direction that they entered, so that the object becomes invisible at that wavelength. This also implies a cancellation of the momentum that would have been given to the object by the radiation. For an object with a typical acceleration of 9.8 ms^{-2} the Unruh wavelength is about 10^{16} m , which seems rather large, but Pendry *et al.* (2007) have proposed metamaterials that can bend the magnetic component of radiation with wavelengths even of this order.

Another way to think about this is that the bending of radiation around the object can be arranged to create a boundary similar to the one considered here to exist at the edge of the observable universe - the size of which is the Θ in equation (1). In the examples here Θ was $2.6 \times 10^{26} \text{ m}$, but for an object surrounded by a carefully arranged metamaterial Θ could be reduced in size, making the inertial drop predicted by equation (1) far more detectable.

Conclusions

A model of modified inertia, using a Hubble-scale Casimir effect predicts orbital velocity jumps near closest approach which are of a similar order of magnitude to the flyby anomalies, except for the NEAR flyby.

The results are extremely sensitive to the Hubble constant, and the numerical schemes used to predict the trajectories were relatively simple. It is therefore hoped that other specialist groups can reproduce these results.

As an experimental test for these ideas it is proposed here that newly-developed metamaterials may be used to reduce the impact of Unruh radiation on an accelerated object, thereby measurably reducing its inertial mass.

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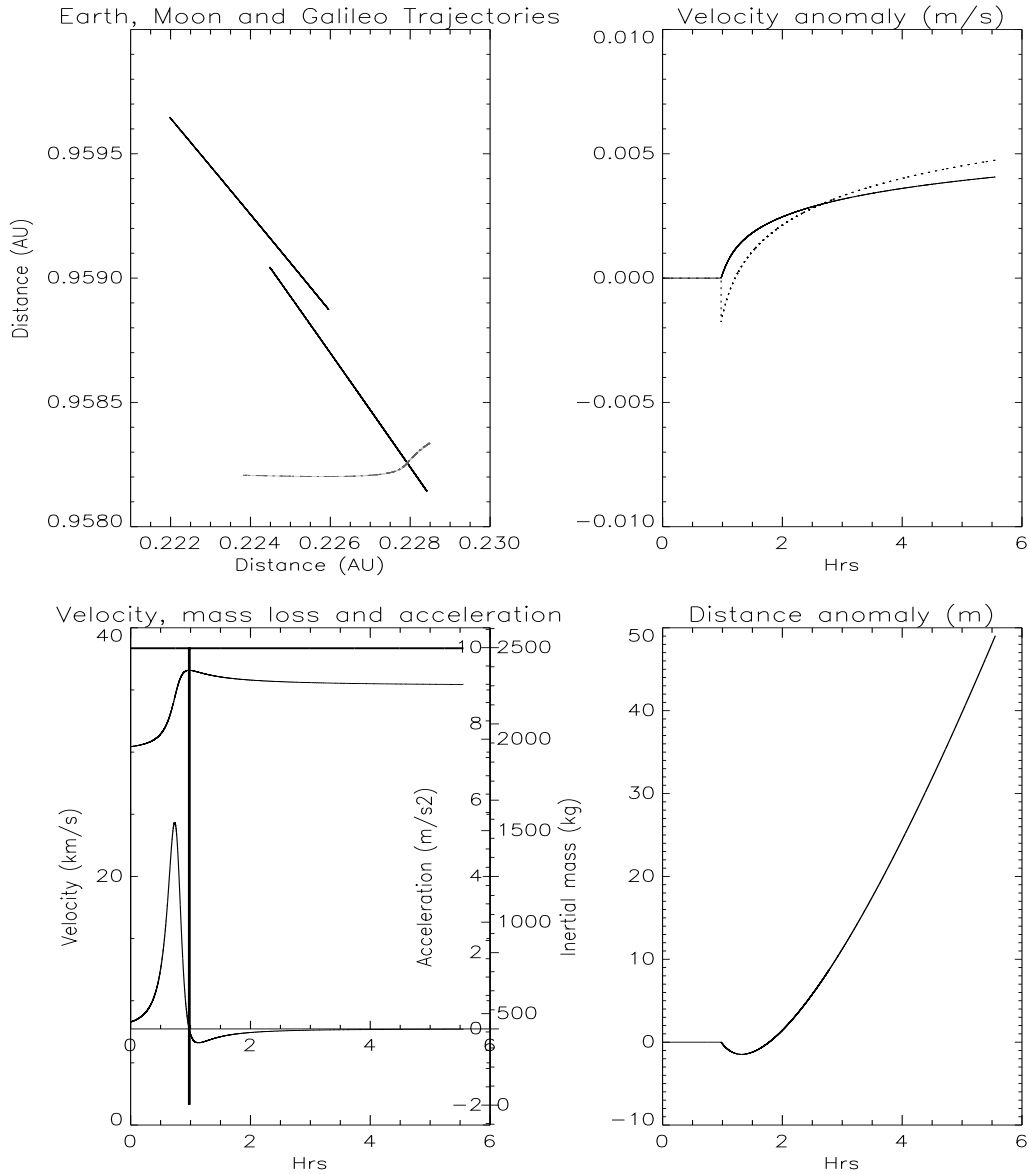


Figure 1. The Earth flyby by Galileo on the 8th December, 1990. Top left: the Earth, Moon and spacecraft trajectories, bottom left: the velocity (km/s), acceleration (m/s²) and inertial mass (kg), top right: the predicted velocity anomaly (m/s), bottom right: the predicted distance anomaly (m).

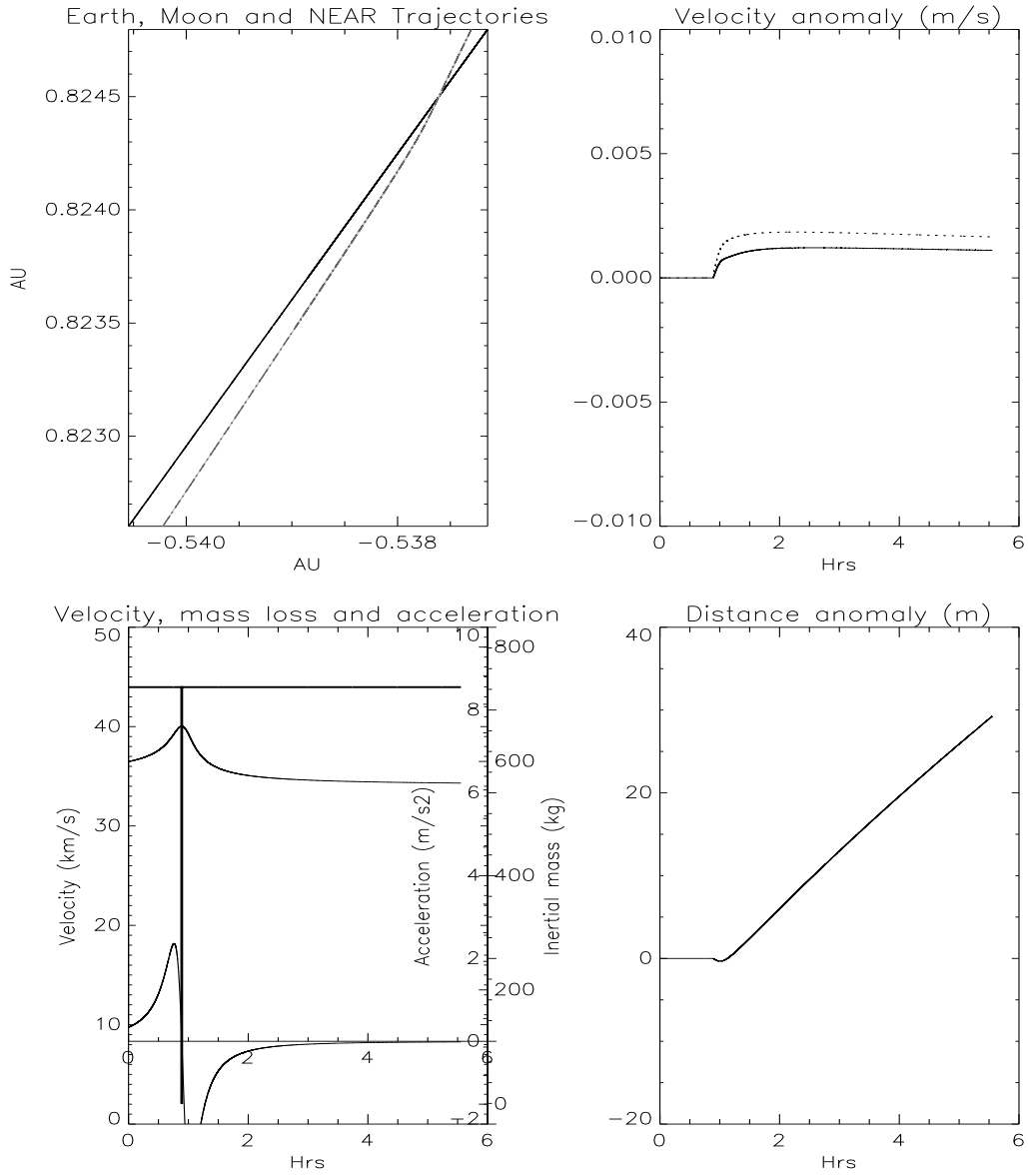


Figure 2. The Earth flyby by NEAR on the 23rd of January, 1998. Top left: the Earth, Moon and spacecraft trajectories, bottom left: the velocity (km/s), acceleration (m/s²) and inertial mass (kg), top right: the predicted velocity anomaly (m/s), bottom right: the predicted distance anomaly (m).

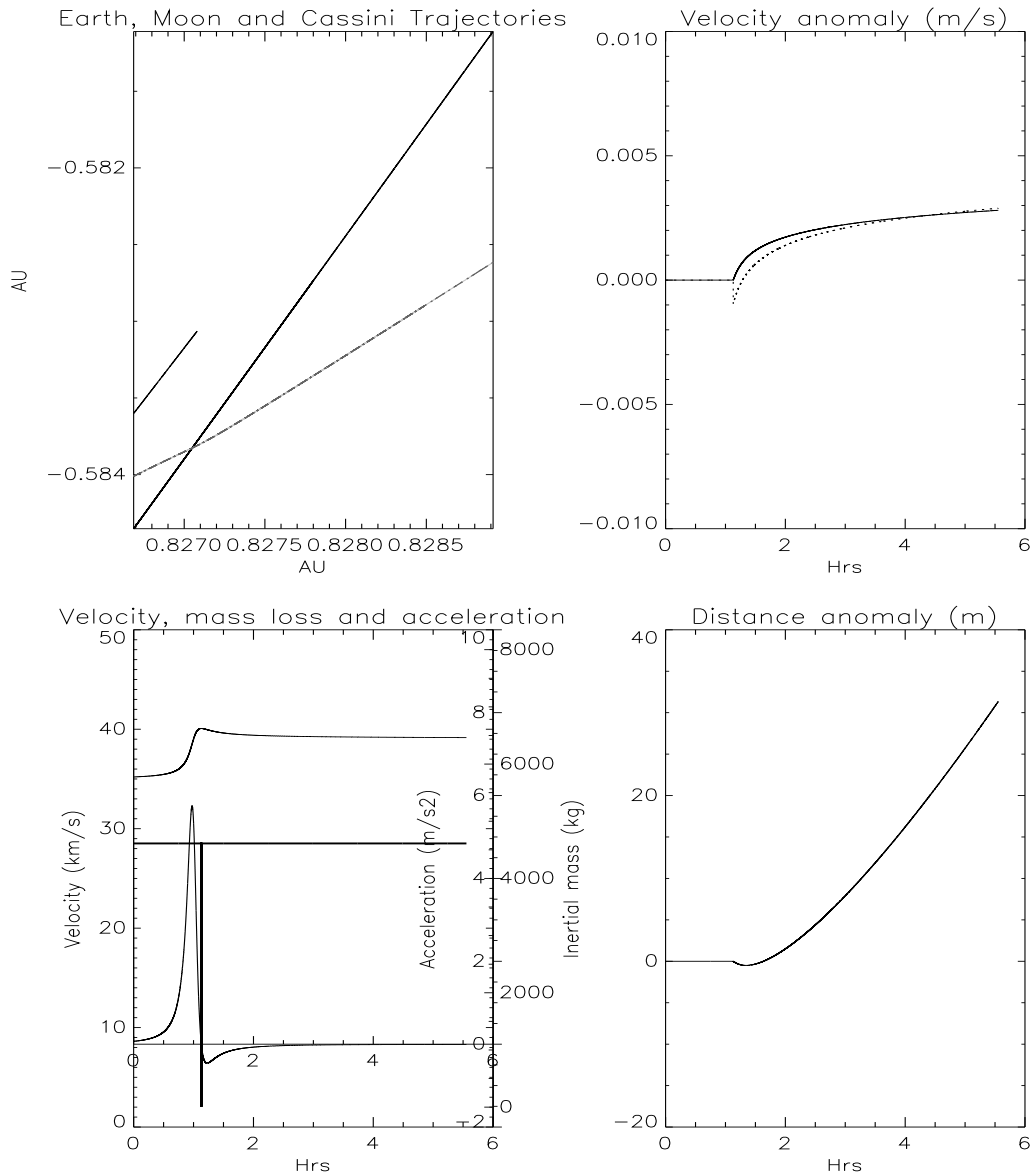


Figure 3. The Earth flyby by CASSINI on the 18th of August, 1999. Top left: the Earth, Moon and spacecraft trajectories, bottom left: the velocity (km/s), acceleration (m/s²) and inertial mass (kg), top right: the predicted velocity anomaly (m/s), bottom right: the predicted distance anomaly (m).

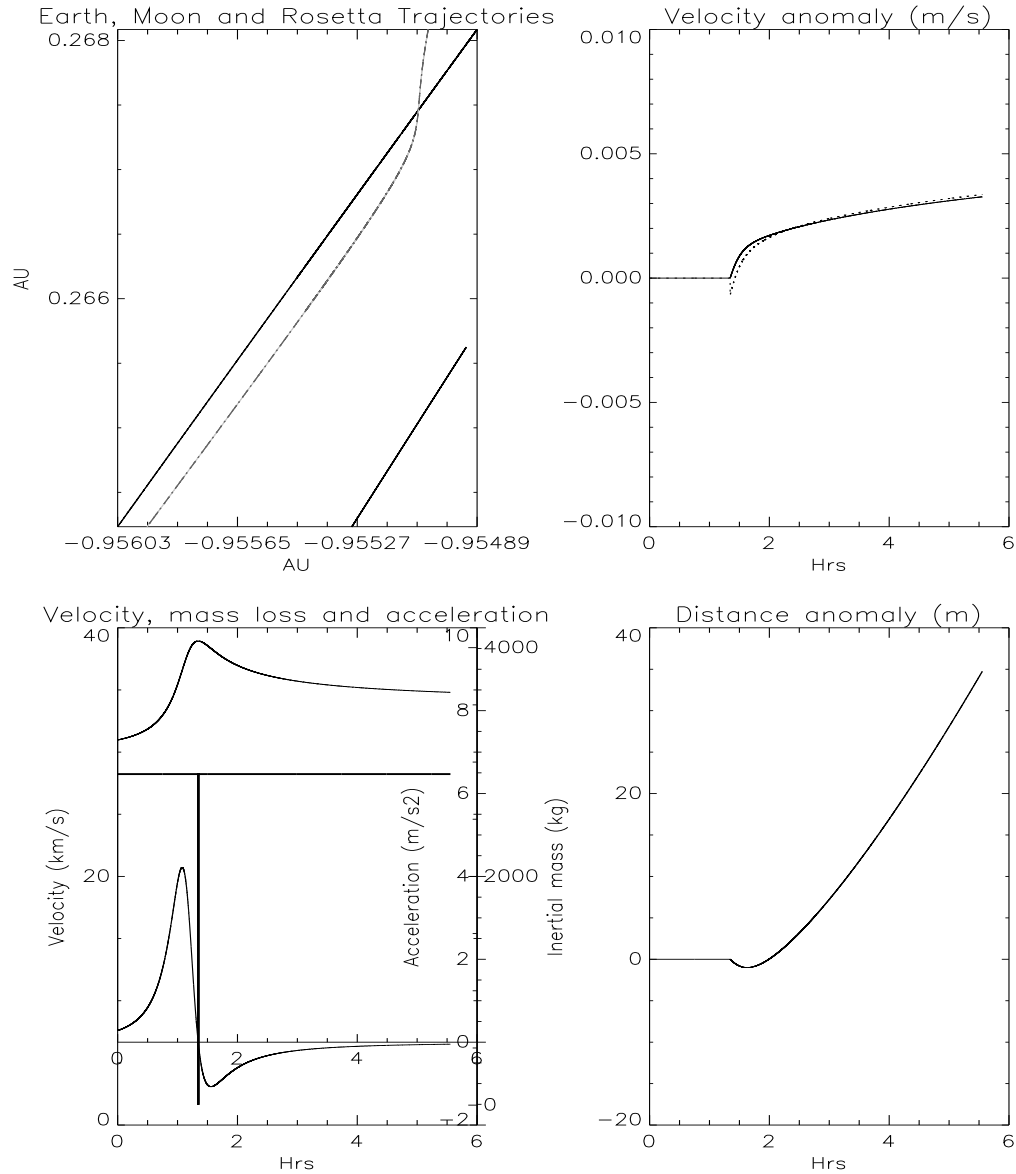


Figure 4. The Earth flyby by ROSETTA on the 4th of March, 2005. Top left: the Earth, Moon and spacecraft trajectories, bottom left: the velocity (km/s), acceleration (m/s²) and inertial mass (kg), top right: the predicted velocity anomaly (m/s), bottom right: the predicted distance anomaly (m).