

COSMIC RADIATION ISSUES FOR THE GRAVITY PROBE B RELATIVITY MISSION GYROSCOPES

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ABSTRACT

We discuss the effects of cosmic radiation on the gyroscopes of the Relativity Mission. These effects are caused by trapped and solar flare protons, and are: charging, heating, momentum transfer, and trapped flux motion in the gyroscope coating. Charging is controlled with photoemitted electrons, and the heating problem is solved by radiation shielding. Gyroscope errors caused by momentum transfer and trapped flux motion are negligible. We conclude that the drift rate of the gyroscopes will not be affected by cosmic radiation.

I. Introduction

The Gravity Probe B Relativity Mission (GP-B) will measure in a 650 km polar orbit the frame dragging (0.033 arcsec/yr) and geodetic (6.6 arcsec/yr) rotational precessions predicted by gravitational theories.¹ Electrostatically suspended gyroscopes (see figure 1) will provide the reference to the local gravitational frame with a precision of better than 0.3marcsec/yr. The main contributions to the radiation environment in this orbit are the charged particles trapped in the Earth's magnetic field² and the charged particles generated by solar flares.³ Note that only the protons affect the gyroscopes, as the shielding provided by the spacecraft stops most electrons. Equation 1a gives a fit to the integral flux of trapped protons as a function of their energy E (MeV), while equation 1b represents the model for the solar flare protons expected for the year 2000, when GP-B is scheduled to fly. Φ_T and Φ_S are averages over all orbits.

$$\Phi_T(E) \cong 7.5 \times 10^6 \cdot \exp(-E/99.6) \text{ protons} \cdot \text{cm}^{-2} \cdot \text{day}^{-1} \quad (1a)$$

$$\Phi_S(E) \cong 7.3 \times 10^7 \cdot \exp(-E/26.5) \text{ protons} \cdot \text{cm}^{-2} \cdot \text{day}^{-1} \quad (1b)$$

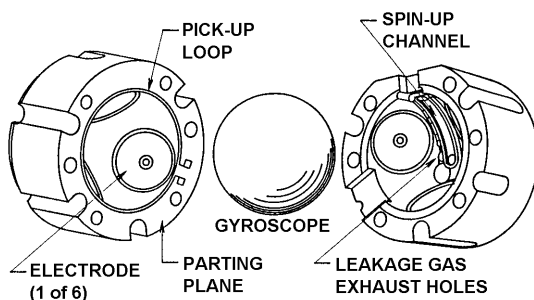


Figure 1. Schematic view of GP-B gyroscope

The energy, charge, and momentum transferred by protons were calculated by two methods; analytically, using the Bethe-Bloch formula, and by Monte Carlo simulation, using the European Space Agency's GEANT radiation transport code.⁴ The results agree in within the calculation errors of about 15%, and confirm that all effects of cosmic radiation on the gyroscopes are due mainly to protons.

A radiation shield of $10 \text{ g}\cdot\text{cm}^{-2}$ was added in order to reduce heating and charging during solar flares, resulting in a total shielding for the gyroscopes of $20 \text{ g}\cdot\text{cm}^{-2}$ aluminium equivalent. Standard space technology is used to mitigate the effects of cosmic radiation on the electronics, the cryogenic probe, and the satellite. However, the gyroscope rotors are mechanically isolated systems spinning in ultrahigh vacuum, thus making it necessary to use non-contact methods for charge control and to rely on thermal radiation for cooling. In the next three sections we discuss the effects of cosmic radiation on the gyroscopes.

II. Gyroscope Charging

Gyroscope requirements, due to torque and acceleration considerations, limit the rotor charge to 15 pC , or equivalently to a 15 mV potential (1 nF rotor capacitance). The total charge accumulation over the 1.5 year mission is about 600 pC making it necessary to use active charge control. Table I gives a summary of the charging rates due to trapped protons (averaged over all orbits) and solar flares (during large flares occurring about 1% of the time), for gyroscopes with and without the additional radiation shield.

Table I. Charging and heating from trapped and solar flare protons.

Shielding	Trapped Protons (All Orbits Average) Charging / Heating	Solar Flare Protons (Flare Duration) Charging / Heating
With Shield ($20 \text{ g}\cdot\text{cm}^{-2}$)	0.007 fA / 1 nW	0.5 fA / 20 nW
Without Shield ($10 \text{ g}\cdot\text{cm}^{-2}$)	0.014 fA / 2 nW	3.0 fA / 200 nW

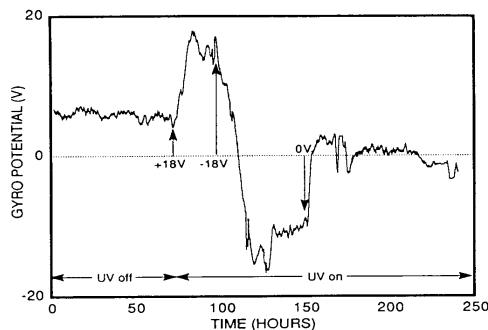


Figure 2. UV charge management test

The rotor charge is measured using a force modulation method which achieves an accuracy of better than 4 mV for an integration time of 100 s . Electrons, generated by photoemission from both the rotor and its housing, can be added or removed from the rotor using a dedicated biasing electrode. Figure 2 shows results of the ground testing of the charge management system, which indicate that it has met GP-B requirements.⁵

III. Gyroscope Heating

Table I gives the calculated power transferred to the rotor by trapped and solar flare protons. At the operating pressure, 10^{-9} Pa at 2.5 K , thermal radiation is the main cooling mechanism for the rotor. Equation 2 gives the rotor temperature T_R as a function of the heating power P and the rotor housing temperature T_H ; where R , ε , and $C \equiv C_0 T^3$ are the rotor's radius, thermal emissivity, and heat capacity, and σ is the Stefan-Boltzmann constant:

$$T_R(t) = T_H^* \left\{ \left[\left(\frac{T_R(0)}{T_H^*} \right)^4 - 1 \right] \cdot e^{-4t/\tau} + 1 \right\}^{\frac{1}{4}} \quad \tau \equiv \frac{C_0 \varepsilon}{4\pi R^2 \sigma} T_H^* \equiv \left(T_H^4 + \frac{P\tau}{C_0} \right)^{\frac{1}{4}} \quad (2)$$

The rotor temperature will be about 3.6 K, (1.1 K above the housing temperature), for 1 nW heat input and the measured emissivity $\varepsilon \cong 0.03$. A three day major solar flare will raise the rotor temperature to about 5.5 K, safely below its 9 K superconducting transition. Note that without the radiation shield the equivalent temperatures would be respectively 4.1 K and 10.0 K.

IV. Momentum Transfer and Trapped Flux Motion

In a worst case estimate of the torques transferred by radiation to the gyroscope we assume an unidirectional flux of protons perpendicular to the spin axis, impinging on one pole of the rotor. This results in a torque of 3×10^{-19} N·m, smaller than the allowable torque of 5×10^{-19} N·m. An exact calculation gives a torque of 10^{-17} N·m, confirming that momentum transfer from radiation is negligible for the GP-B gyroscopes.

Local heating of the 1.3 μm niobium coating of the rotor by protons can cause trapped flux motion, and thus disturb the readout system. Modeling the heating as an instantaneous line source, we calculate the maximum motion of a fluxon to be about 0.1 μm , and the number of flux jumps to be approximately 10 per year. This is well below the level of 10^3 flux jumps per year which would double the readout error.

VI. Conclusions

Charge management, using measurement by force modulation and electrons generated by ultraviolet photoemission, are the solutions for the GP-B gyroscope charging problem. The effective thermal emissivity of the gyroscopes was measured to be about 3%. For this emissivity, and with $20 \text{ g}\cdot\text{cm}^{-2}$ aluminium radiation shielding, the rotor temperature remains well below its superconducting transition temperature. Torques and trapped flux motion induced by protons cause negligible errors. In conclusion, the GP-B gyroscope performance will not be degraded by cosmic radiation.

Acknowledgments

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