ROYAL CANADIAN AIR CADETS

PROFICIENCY LEVEL FOUR

INSTRUCTIONAL GUIDE

SECTION 11

EO C440.09 – DESCRIBE THE RELATIONSHIP BETWEEN GRAVITY AND SPACE-TIME

Total Time: 60 min

PREPARATION

PRE-LESSON INSTRUCTIONS

Resources needed for the delivery of this lesson are listed in the lesson specification located in A-CR-CCP-804/PG-001, *Proficiency Level Four Qualification Standard and Plan*, Chapter 4. Specific uses for said resources are identified throughout the instructional guide within the TP for which they are required.

Review the lesson content and become familiar with the material prior to delivering the lesson.

Obtain and cue the following six Windows Media Video (WMV) files from Reference C3-312 located at http://einstein.stanford.edu/index.html

- WMV file Newtons_Universe_Anima,
- WMV file Einsteins_Universe_Anima,
- WMV file Rel_gyro_expt-anima,
- WMV file *SConSquid*,
- WMV file Simple_expt_anima, and
- WMV file *DF-Satellite*.

Create slides of figures located at Attachment A.

Photocopy the Gravity and Space-Time handout located at Attachment B for each cadet.

Obtain a copy of Reference C3-310, *Gravity Probe B: An Educator's Guide*.

Obtain and cue the *Testing Einstein's Universe* DVD.

Obtain a large round coin, such as a Canadian two-dollar piece, for use in TP 2.

PRE-LESSON ASSIGNMENT

Nil.

APPROACH

An interactive lecture was chosen for TPs 1 and 2 to introduce theories of gravitation and give an overview of the Gravity Probe B mission.

An in-class activity was chosen for TPs 3 and 4 as it as it is an interactive way to reinforce the relationship between gravity and space-time, provoke thought, and stimulate interest among cadets.

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INTRODUCTION

REVIEW

Nil.

OBJECTIVES

By the end of this lesson the cadet shall be expected to describe the relationship between gravity and space-time.

IMPORTANCE

It is important for cadets to describe the relationship between gravity and space-time because viewing gravity as a curvature of space-time explains more phenomena in the aerospace environment than the classical Newtonian view of gravity as a force of attraction.

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Teaching point 1 **Compare early ideas of gravity to gravitation under the theory of relativity.**

Time: 10 min Method: Interactive Lecture

NEWTON'S UNIVERSAL LAW OF GRAVITATION



Show the cadets the WMV file *Newtons_Universe_Anima*.

Running time is 1 minute, 8 seconds.

GRAVITY AS A FORCE BETWEEN MASSES

According to Newton's theory of gravity, all bodies possess the force of attraction called gravity. Larger masses, such as the Sun, attract smaller masses, such as the planets and comets, more strongly, causing the smaller masses to move toward the larger masses. In our solar system, the planets orbit the Sun due to the force of the Sun's gravity pulling them into this elliptical path. Comets soaring through the galaxy are curved toward the Sun due to gravity's pull.

INSTANTANEOUS TRANSMISSION OF GRAVITY

In *Principia* (1687), Newton stated, "there is a power of gravity pertaining to all bodies, proportional to the several quantities of matter which they contain." However, when Newton was questioned about how this "power of gravity" transmitted from one body to another, he responded, "I make no hypothesis."

Einstein, along with other scientists, began to question this conclusion around the turn of the 20th century. In the 19th century, Maxwell had shown that light propagated at a finite rate in a vacuum; 299 792 km / sec (185 871 miles / sec). In 1905, Einstein's theory of special relativity was based on the idea that this rate was the speed limit for all matter and energy in the universe. If gravity was a force that transmitted between masses in the same way light propagated through space, the force of gravity should be equally restricted to 299 792 km / sec. While moving nearly 300 000 km each second is extremely fast, it is not instantaneous.

THE INTERDEPENDENCE OF SPACE AND TIME

Newton believed that space and time were absolute or fixed entities and that gravity could be represented as an attractive force that somehow acted instantaneously between objects. Einstein determined that space and time are relative entities, interwoven into a "fabric," which he called space-time, and he realized that no force —not even gravity—could act faster than the speed of light. In Einstein's universe, the presence of celestial bodies causes space-time to warp or curve; and gravity is not a force, but rather the product of bodies moving in curved space-time.

Since space and time were separate concepts in Newton's physics, an object's position is simply described by three spatial coordinates. In Einstein's physics, space and time are combined into space-time so that when describing the position of an object one must include all four dimensions—the three spatial dimensions and time. The passage of time is relative to motion, so the time coordinate in the description of position describes time relative to a frame of reference, which is absolutely critical in Einstein's relativity.

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CURVATURE OF SPACE-TIME



Show the cadets the WMV video file *Einsteins_Universe_Anima*.

Running time is 1 minute, 9 seconds.

In 1916, Einstein presented the world with this new understanding of the universe—his general theory of relativity. In his theory, space is not an empty void, but an invisible structure called space-time. Nor is space simply a three-dimensional grid through which matter and light and energy move. It is a four-dimensional structure called space-time whose shape is curved and twisted by the presence and motion of matter and energy.

Space-time curves around any mass. The presence of planets, stars and galaxies warps the fabric of space-time in a manner similar to a bowling ball warping a spandex sheet. The mass of the ball stretches the fabric and creates a dip or curve that gradually decreases the further one moves from the mass.

When a mass passes near a larger mass, it accelerates toward the larger mass because space-time itself is curved toward the larger mass. The smaller mass is not “attracted” to the larger mass by any force. The smaller mass simply follows the structure of curved space-time near the larger mass. For example, the massive Sun curves space-time around it, a curvature that reaches out to the edges of the solar system and beyond. The planets orbiting the Sun are following the curvature of space-time by the Sun.



Show the cadets the WMV file *Rel_gyro_expt-anima*.

Running time is 3 minutes, 1 second.

CONFIRMATION OF TEACHING POINT 1

QUESTIONS:

Q1. What was the speed limit for all matter and energy in the universe under Einstein's 1905 Special Theory of Relativity?

Q2. How many coordinates describe an object's position in Newton's physics?

Q3. How many coordinates describe an object's position in Einstein's physics?

ANTICIPATED ANSWERS:

A1. The speed of light propagating at a finite rate in a vacuum: 299 792 km / sec (185 871 miles / sec).

A2. In Newton’s physics, an object's position is simply described by three spatial coordinates.

A3. In Einstein’s physics, space and time are combined into space-time so that when describing the position of an object one must include all four dimensions—the three spatial dimensions and time.

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Teaching point 2 **Describe the Gravity Probe B (GP-B) mission.**

Time: 10 min Method: Interactive Lecture

GYROSCOPE OPERATION

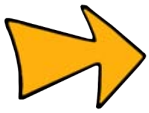
The gyroscope is a spinning wheel (rotor) in a universal mounting (gimbal) that allows its axle to be pointed in any direction.

Also known as rigidity in space, gyroscopic inertia is the tendency of a rotating object to remain in its plane of rotation. This allows the spin axis of a gyroscope to remain unchanged regardless of how the gimbal is moved around it.



Show the cadets the slide of Figure A-1 located at Attachment A.

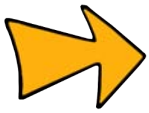
Examples of rotating objects that exhibit rigidity in space are tops, gyroscopes, Frisbees, basketballs and any spinning planet. These objects tend to maintain their orientation in space.



Aircraft use gyroscopes for navigation, with the gyroscope maintaining the orientation of the universe so that relative changes in the aircraft's orientation can be measured.

In the Gravity Probe B (GP-B) satellite, the gyroscope maintains its orientation relative to a distant guide star so that the changes in the orientation of space-time near Earth can be measured.

To work properly, the rotor must be kept spinning at a constant speed. Gyroscopic instruments may be powered by one or more power sources. In an aircraft, a gyroscope can be powered by moving air systems. In the GP-B satellite, the gyroscopes are powered by helium gas that is stored as liquid in the largest satellite component: the dewar.



Dewar. A double-walled vessel with a vacuum between the walls to reduce the transfer of heat, used for storing hot or cold liquid.



Show the cadets the slide of Figure A-2 located at Attachment A.

THE SPIN AXIS OF A GYROSCOPE



Spin a coin on its edge to show the cadets that it will remain upright while spinning. Demonstrate that the coin will not remain upright on its edge when it is not spinning.

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It was predicted that the spin axis of each of GP-B's four gyroscopes move with the curvature and twist of local space-time around Earth. The only way this motion can be detected is by comparing each spin axis to a fixed line of reference. In this mission, the fixed reference line is the line between the telescope and the guide star: IM Pegasi. The telescope has to remain fixed on the exact centre of the guide star (within one milliarcsecond, or 1 millionth of an inch) throughout the mission or GP-B would lose its single critical reference line.



SQUID (Superconducting QUantum Interference Device). A device that monitors the spin axis orientation of the supercooled, superconducting gyroscope's perfectly unmarked, spherical rotor—without exerting significant torque on the spinning rotor.



Show the cadets the WMV video file *SConSquid*.

Running time is 2 minutes, 12 seconds.

GEODETIC EFFECT

Einstein’s theory predicted that the presence of a mass in space, such as the Earth, will warp local space-time, creating a dip or curve in space-time. This is called geodetic effect.

FRAME-DRAGGING EFFECT

One of the predictions of Einstein’s general theory of relativity is that local space-time is twisted by the rotation of the Earth—any rotating mass will drag the local space-time frame of reference with it. The predicted drag is very small and fades as one travels further from the rotating mass, but the twist nearby can affect the paths of light, energy, and other masses.



Show the cadets the WMV video file *Simple_expt_anima*.

Running time is 1 minute, 7 seconds.

SPACECRAFT COMPONENTS

The GP-B satellite is composed of thousands of components, but the mission can be understood by considering only a few, to include:

- dewar,
- gyroscopes,
- star tracking telescope, and
- micro thrusters.



Show the cadets the WMV video file *DF-Satellite*.

Running time is 4 minutes 25 seconds.

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CANADA'S CONTRIBUTION TO ORIENTATION CONTROL

Astrophysicists at York University measured and tracked the movement of GP-B's guide star, IM Pegasi, against a backdrop of more distant quasars. This allowed minute changes in the position of IM Pegasi to be taken into account when changes in gyroscope orientation was measured—in a system where angles of a millionth of a degree are of critical importance.



Quasar. Any of a class of starlike celestial objects, apparently of great size and remoteness, often associated with a spectrum with a large red shift and intense radio emission.

CONFIRMATION OF TEACHING POINT 2

QUESTIONS:

Q1. What is meant by rigidity in space?

Q2. What is geodetic effect?

Q3. What is frame-dragging effect?

ANTICIPATED ANSWERS:

A1. Rigidity in space is the tendency of a rotating object to remain in its plane of rotation.

A2. One of the predictions of Einstein’s theory; the presence of a mass in space, such as the Earth, will warp local space-time, creating a dip or curve in space-time.

A3. One of the predictions of Einstein’s general theory of relativity; local space-time is twisted by the rotation of the Earth.

Teaching point 3 **Have the cadets watch *Testing Einstein's Universe*.**

Time: 25 min Method: In-Class Activity

ACTIVITY

OBJECTIVE

The objective of this activity is to have the cadets learn about the GP-B mission by watching *Testing Einstein's Universe* while finding answers to assigned questions.

RESOURCES

- Testing Einstein's Universe DVD,
- Gravity and Space-Time handout located at Attachment B for each cadet,
- Paper, and
- Pens / pencils.

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ACTIVITY LAYOUT

Nil.

ACTIVITY INSTRUCTIONS

1. Distribute the Gravity and Space-Time handout located at Attachment B to each cadet.

2. Instruct the cadets to record their answers to the questions in the Gravity and Space-Time handout while watching *Testing Einstein's Universe*.

3. Have the cadets watch *Testing Einstein's Universe*.

SAFETY

Nil.

CONFIRMATION OF TEACHING POINT 3

The cadets' participation in the activity will serve as the confirmation of this TP.

Teaching point 4 **Conduct an activity to correct answers to the assigned questions.**

Time: 5 min Method: In-Class Activity

ACTIVITY

OBJECTIVE

The objective of this activity is to have the cadets check their answers to the questions at Attachment B.

RESOURCES

- Reference C3-310, *Gravity Probe B: An Educator's Guide*,
- Answer Key—Gravity And Space-Time located at Attachment C, and
- Completed Gravity and Space-Time handouts.

ACTIVITY LAYOUT

Nil.

ACTIVITY INSTRUCTIONS

1. Using the answer key located at Attachment C, read the answer to the question.

2. Have the cadets confirm their answer. If required, discuss any discrepancies, referring to Reference C3-310 as necessary.

3. Repeat Steps 1 and 2 for each question.

SAFETY

Nil.

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CONFIRMATION OF TEACHING POINT 4

The cadets' participation in the activity will serve as the confirmation of this TP.

END OF LESSON CONFIRMATION

The cadets' participation in watching *Testing Einstein's Universe* will serve as the confirmation of this lesson.

CONCLUSION

HOMEWORK / READING / PRACTICE

Nil.

METHOD OF EVALUATION

Nil.

CLOSING STATEMENT

The relationship between gravity and space-time is still theoretical. However, the relativistic theory of gravity as a manifestation of the curvature of space accounts for more natural phenomena than the classical Newtonian explanation.

INSTRUCTOR NOTES / REMARKS

Nil.

REFERENCES

C3-310 Range, S. K. (2004). *Gravity Probe B: An educator's guide*. Washington, DC: NASA. Retrieved February 6, 2009, from http://einstein.stanford.edu/RESOURCES/education-index.html#guide

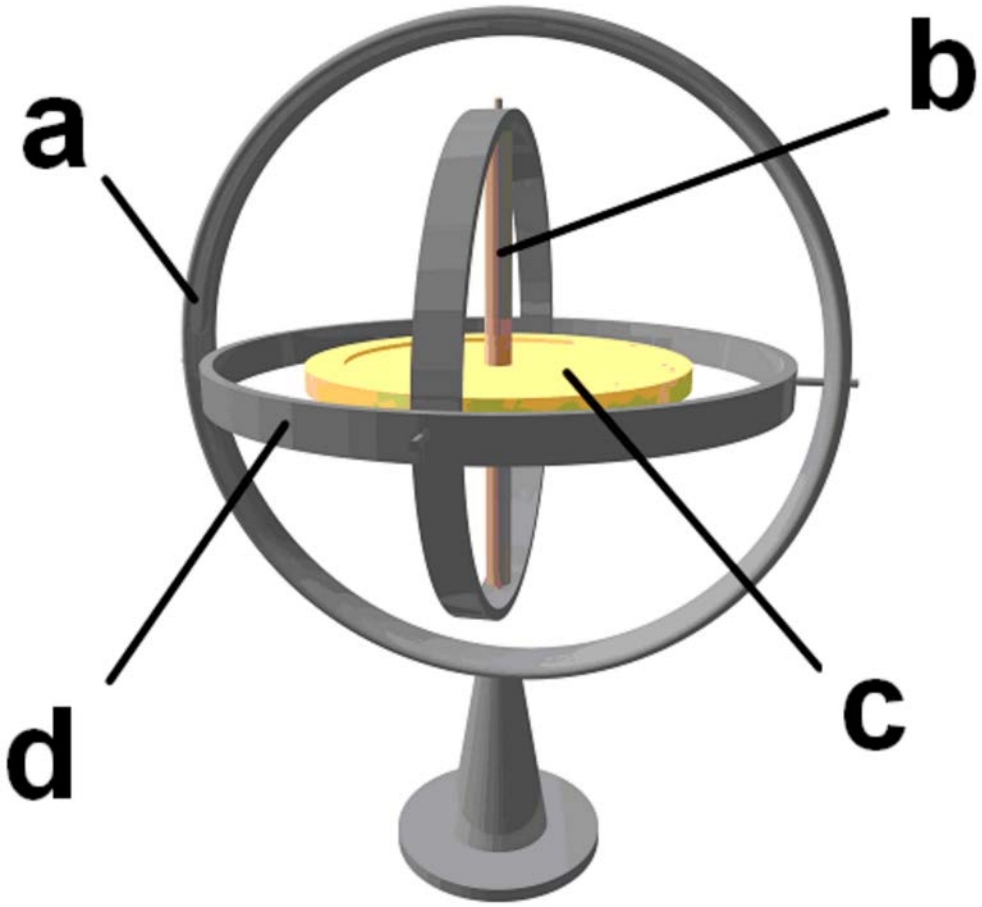
C3-311 Bartel, N. (Producer & Director). (2003). *Testing Einstein's universe* [Motion picture]. Canada: York University.

C3-312 Range, S. K. (2008). *Gravity Probe B: Testing Einstein's universe*. Retrieved February 6, 2009, from http://einstein.stanford.edu/index.html

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Note. From "3D Gyroscope", Wikimedia. Retrieved November 18, 2008, from http://upload.wikimedia.org/wikipedia/commons/e/e2/3D_Gyroscope.png

Figure A-1 Gyroscope

a. Gyroscope frame

b. Spin axis

c. Rotor

d. Gimbal

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Note. From Gravity Probe B: An Educator's Guide, (p. 30), by S. Shannon, 2004. Washington, DC: NASA.

Figure A-2 Gravity Probe B Dewar

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GRAVITY, SPACE-TIME AND GP-B

Q1. Name two 20th century tests of Einstein's general theory of relativity.

- _____
- _____

Q2. Why was Gravity Probe B placed into a low orbit even though that meant it would be buffeted by the upper atmosphere?

_____

_____

Q3. Why was Gravity Probe B placed into a polar orbit?

_____

_____

Q4. What were three uses of the liquid helium in Gravity Probe B's dewar?

- _____
- _____
- _____

Q5. In Einstein's Equivalence Principle, what is said to be equivalent?

_____

_____

Q6. What is the significance of Gravity Probe B's drag-free status?

_____

_____

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ANSWER KEY—GRAVITY, SPACE-TIME AND GP-B

Q1. Name two 20th Century tests of Einstein's general theory of relativity.

A1. Reference C3-310 (pp. 13–14): Any two of:

- precession of Mercury's orbit,
- starlight deflection during a solar eclipse,
- gravitational redshift, and
- shapiro time delay.

Q2. Why was Gravity Probe B placed into a low orbit even though that meant it would be buffeted by the upper atmosphere?

A2. Reference C3-310 (p. 32): The effects of local space-time (its curve and twist) weaken dramatically as one moves farther from the Earth. Gravity Probe B was given an orbit that would get it as close to the Earth as possible, to see the space-time effects more clearly.

Q3. Why was Gravity Probe B placed into a polar orbit?

A3. WMV file *Rel_gyro_expt-anima*: In a polar orbit the two effects, geodetic and frame-dragging, occur at right angles, providing maximum separation. This makes it possible for a gyroscope to measure both effects simultaneously.

Q4. What were three uses of the liquid helium in Gravity Probe B's dewar?

A4. Three uses of the helium in Gravity Probe B's dewar include:

- Reference C3-310 (p. 25): Spinning the gyroscopes,
- Reference C3-310 (p. 30): Supercooling the instruments, and
- Reference C3-310 (p. 32): Powering the micro-thrusters.

Q5. In Einstein's equivalence principle, what is said to be equivalent?

A5. Reference C3-310 (p. 25): An experience of gravity is equivalent to an experience of acceleration.

Q6. What is the significance of Gravity Probe B's drag-free status?

A6. Reference C3-310 (p. 29): The slightest amount of heat or pressure, the influence of a magnetic field, any kind of gravitational acceleration, or the tiniest amount of atmospheric turbulence will destroy the accuracy of the instrument.

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